A THREE-DIMENSIONAL STUDY OF THE CRANIOFACIAL GROWTH AND DEVELOPMENT OF SIXTEEN FEMALE BOLTON FACES

by

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Submitted in partial fulfillment of the requirements for the Degree of Master of Science in Dentistry

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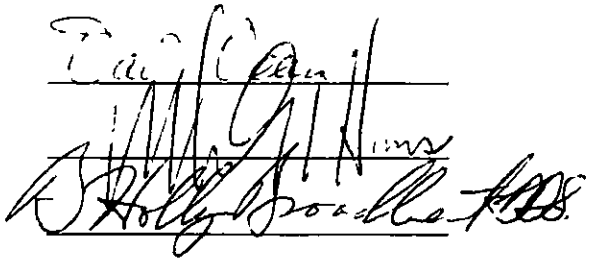
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Abstract

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The invention of the Broadbent-Bolton cephalometer in 1925 made clear the possibility of collecting three-dimensional data from biorthogonal plain film head x-rays (cephalograms). The first purpose of this study was to use this technology to capture three-dimensional landmark coordinates from sixteen female series of lateral and frontal (posteroanterior) plain film head x-rays taken of participants in the Bolton Study. The sixteen individuals were chosen from the Bolton Face sample of individuals presenting Class I Angle molar relationship. This data was collected with the aid of a computer program, 3dCEPH, developed for this purpose.

The second objective of this study was to describe and analyze shape changes found in Procrustes comparisons of adjacent age groups (i.e., between sets of averaged

landmarks). The Procrustes distance units at each landmark were summed within specific groups of landmarks representing five craniofacial regions. Morphological change in each region is described separately, through time (ages 3-18) and for its relative contribution to craniofacial shape change as a whole.

Overall, continuous shape modification of the craniofacial complex, usually peaking in the earliest age groups is observed. The maxilla undergoes its greatest period of shape modification during the 7-8 year old period, showing a significant slowing thereafter. On the other hand, the mandible, following two early growth spurts (age 3-4, 7-8), shows three additional shape change peaks (11-12, 14-15, and 17-18). The lattermost period has been referred to as "late growth". The anterior and posterior vault show a trend toward the center of the head, corresponding to overall rounding remodeling in those regions. In the mid-face the orbit demonstrates no significant anteroposterior movement, unlike the rest of the landmarks forming the mid-facial region. This results in a slight protrusion of the adult forehead and mid-face, coincident with dental protrusion.

With the eventual addition of male data, three-dimensional information from the Bolton Study can play an important role in craniofacial patient: diagnosis, treatment planning, prosthetic design, stereotactic procedures, and procedural outcome assessments.

DEDICATION

To my parents, Jorge Alberto Palomo and Maria Cristina Sere de Palomo, my brothers, Pablo, Manuel, and Antonio Palomo, and grandparents, Dora H. Berreta, Jorge Sere del Campo and Maria Carolina Naguila de Sere. Thank you for all the love and support.

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INTRODUCTION

The Bolton-Brush Growth Study (BBGS) is the largest and perhaps best known longitudinal study of craniofacial growth and development (Bailey 1992; Subramanyan, Dean 1996). It is also part of the Cleveland area's history. Close to six thousand BBGS participants were recruited from the Cleveland area between 1928 and 1959.

It was at the Department of Anatomy of the Western Reserve University (now Case Western Reserve University) School of Medicine that the BBGS began as two separate studies, the "Brush Inquiry", designed to chart the physical and mental progression of the normal child, and the "Bolton Study of the Development of the Face of the Growing Child", which focused on normative human craniofacial development. Eventually, the BBGS moved to the Case Western Reserve University School of Dentistry, where a recall of Bolton Study participants is currently underway.

The Brush Inquiry began on May 29, 1929, but its methods and procedures were already in use in 1928. Dr.

T. Wingate Todd directed the Brush Inquiry, receiving primary funding support from Charles Francis Brush, founder of the General Electric Corporation.

The primary objective of the Brush Inquiry was to study the growth and development of the normal child. This, according to Todd, could be best achieved if done using healthy and live children. The sub-adult cadaver population available to him was made up primarily of children presenting congenital birth defects, growth insults, or pathologically induced "wasting" (Todd 1931). Dr. Todd's objectives may be best described in his own words:

> ". . .the opportunity to investigate developing organs under favorable circumstances, and anatomy plus radiography and observation of healthy children. . . forward from the cradle, not backward from the morgue (Behrents 1984)."

Through the use of health contests, children were enrolled in the BBGS. Once enrolled, attempts were made to examine them annually following a protocol prepared by Dr. Todd. The data collected from Brush Inquiry participants was organized in five different areas:

1. Physical

    a) List of body measures (25)

b) Radiographs of 6 skeletal areas:

1. hand
2. elbow
3. shoulder
4. hip
5. knee
6. foot

2. Mental

a) Psychological tests (40 different mental, skill, aptitude and personality tests)

b) Behavioral tests (a 588-entry questionnaire)

3. Functional Health Inquiry

a) Family physician reports

b) Hand-eye coordination tests

c) Psychomotor development

d) Food preference inquiry

e) Strength of muscle test

f) Foot prints in weight bearing and sitting

4. Genetic and Environmental Inquiry Questionnaires about:

a) personal and family education

b) health status

c) familial illnesses tendencies

d) occupation

e) recreation.

5. Dentofacial

a) Photographs

b) Tooth and mouth conditions

c) Unique radiographs of jaw alignment

d) Tooth impressions

Data collection was performed at different time intervals, depending on the child's age group. Infants (0-1 year of age) were examined every three months, young children (1-5 years old) every six months, and older children every year on or about their birthday.

After Todd's death in December of 1938, the direction of the Brush Inquiry passed to Dr. William Walter Greulich. Greulich directed the Brush Inquiry until 1942 when, mostly because of reduced funding, lack of x-ray film, and technical help, it was decided to transfer all the Brush Inquiry records to the Bolton Study and discontinue further data collection. Under Greulich's direction, the transferred Brush Inquiry data was studied and findings were prepared for publication. From 1928-1942 the Brush Inquiry recruited close to four

thousand children, from whom a quarter million x-rays were taken, twenty-two thousand physical examinations were recorded and ninety thousand mental and psychological tests were performed. Of these four thousand children, 2890 were also enrolled in the "Bolton Study" (Hans, Broadbent, Nelson 1994).

The "Bolton Study of the Face of the Growing Child", more commonly known as the "Bolton Study", like the Brush Inquiry, started in 1928 and had one major source of funds, the Bolton family, especially Frances Payne Bolton and her son, Charles Bingham Bolton. Charles Bolton personally assisted in the radiographic data collection portion of the Bolton Study. The Bolton Study, initially independent, was coordinated with the Brush Inquiry. Both studies shared most of their participants.

The Bolton Study was conducted under the direction of Dr. B. Holly Broadbent, Sr. Its primary intent was to determine what occurred in the facial skeleton and dental arcade during growth and development.

The visit frequency requested for the Bolton participants was the same as that at the Brush Inquiry. The examinations and records taken were limited to:

1. Anthropometric measurements.
2. Dental impressions.
3. Lateral and frontal (anteroposterior) plain film head radiographs.
4. Hand-wrist radiographs.

The active enrollment of participants continued until 1959, when it was decided to dedicate more time to assessment and study of the information collected.

Dr. B. H. Broadbent, Sr. continued as the Bolton Study Director until 1969, when he retired for health reasons. His son, Dr. B. H. Broadbent, Jr., who had joined the BBGSC faculty in 1952, became and continues today as the Bolton Study Director.

Like the Brush Inquiry, the number of participants in the Bolton Study is impressive. The number of subjects has reached 4,309, from which approximately fifty thousand dental impressions and close to forty-four thousand head x-rays were taken.

The combined data of both the Brush Inquiry and the Bolton Study, now resides in the Bolton-Brush Growth Study Center at CWRU. Recently the Geoffrey Walker cephalometric collection was contributed to the BBGSC (Nelson, Hans, Broadbent 1997). In fact it is the

cephalometric data of the "Bolton Study", its twenty-two thousand biorthogonal pairs of plain film x-rays documenting the growth and development of the human head, which is its most actively used portion today.

Traditionally, the plain film head x-rays of the Bolton Study have been traced. Tracing produces two-dimensional contour and landmark diagrams of the skull and dentition. These tracings have most often been statistically analyzed as a series of linear distances, angles, perimeter, and indices thereof.

The primary goal of this thesis was to use a portion (sixteen) of the female Bolton Study series to collect three-dimensional landmarks. A description of the landmark shifts from year to year, for ages 3-18, is provided.

LITERATURE REVIEW

Orthodontic diagnosis of growing children and outcomes assessments often involves comparison of patient's radiographs with the physician's perception of normality. A subjective endeavor by definition, the variation between practitioners often leads to the desire for a second opinion. While the large scale pattern of craniofacial growth and development are generally known (Enlow, Harris 1964; Moyers, Bookstein 1979), there is still need for a tangible, material, and statistical way of visualizing normality.

Modern statistics owes its origin largely to attempts to measure and describe craniofacial anatomy. The history of craniometry in growth studies can be divided into four stages, earliest to latest: first, craniometry by caliper measurements (dry skull only), which was cross sectional (different individuals in each cohort) but which could be represented three dimensionally; second, soft tissue cephalometry (on live human heads) which was longitudinal but could also be

represented three dimensionally; third, roentgenographic cephalometry (projection x-ray head films), which is longitudinal but which in practice is two dimensional; and most recently, digital tomographic cephalometry (plain film x-ray, CT, MR) which is longitudinal and, once more, three dimensional (Maganzini 1974; Dean et al. 1997).

The earliest interest in radiographically based cephalometry was taken by Dr. B. H. Broadbent, Sr. He became interest in craniofacial growth and development as a student of Dr. T. Wingate Todd. Working with Dr. Todd in 1924, Dr. Broadbent added a metric scale to Todd's craniostat (an instrument used to hold a dry skull in a fixed position), and turned it into a craniometer, which permitted direct measurements of dentofacial structures (Bailey 1992). In 1925, Broadbent added a x-ray film holder to the craniometer, making it into a roentgenographic craniometer, and making possible the standardized collection of dry skull cranial x-rays.

In 1926, Broadbent developed the roentgenographic cephalometer. It holds the head of a living subject in a fixed position, while precise and reproducible lateral and posteroanterior (frontal) radiographs are taken. In

later studies, Broadbent more fully developed suggested a standard protocol by which frontal and lateral head x-rays could be taken clinically (Broadbent 1931).

This device, the Broadbent-Bolton roentgenographic cephalometer, became the primary data collection device for several craniofacial growth studies (Table 1).

TABLE 1.--Longitudinal Growth Studies that used the Broadbent-Bolton Cephalometer

Study	Reference
The Bolton Study	(Broadbent et al. 1975)
The Burlington Growth Study	(Popovich, Thompson 1977; Saunders et al. 1980)
The Michigan Growth Study	(Primack 1978; Ackerman 1979)
The Belfast Growth Study	(Kerr 1979)
The Philadelphia Growth Study	(Krogman, Sassouni 1957)
The Denver Growth Study	(Sherman et al. 1988)
The Fels Research Institute Study	(Lewis et al. 1985)
The Forsyth Twin Study	(Medicus et al. 1971)
The Iowa Child Welfare Study	(Bishara et al. 1985)
The Matthews Implant Collection	(Baumrind et al. 1987)
The Meharry Growth Study	(Richardson 1991)
The Montreal Growth Study	(Buschang, Tanguay 1989)
The Oregon Growth Study	(Buck, Brown 1987)

Broadbent began a longitudinal data collection for the "Bolton Study of the Development of the Face of the Growing Child" in 1927. However, the study did not officially commence until 1928. After closing the data collection in 1959, he selected what he would call the Bolton Faces from a series of 4,309 children that had

contributed frontal and lateral head films during the thirty-one year (1928-1959) Bolton-Brush Growth Study.

The following criteria of "normality" were established as the framework for the Bolton Face selection process:

1. Excellence of static occlusion as viewed on the dental study casts and cephalometric radiographs.

2. A good health history, which precluded those who had significant debilitating diseases from becoming part of the group.

3. Faces that conformed in a favorable manner to the statistically derived mean of craniofacial measurements.

4. Aesthetically favorable faces as viewed arbitrarily by the Bolton Study Board of Managers.

5. Availability of long-term records, which would mean that the individual case was recorded annually from 1 year to 18 years of age on a longitudinal basis (Broadbent et al. 1975).

The published Bolton Standards included thirty-two people (sixteen males and sixteen females). One operator, William H. Golden, produced all the lateral and posteroanterior radiograph tracings (Miyashita 1996). He condensed all bilateral (right and left) structures seen in the lateral view into a single central outline. After that, all the tracings were divided into age groups. The

next step was the averaging process, in which pairs of tracings in each age cohort were superimposed to produce a third tracing which would then be averaged using the same technique to the next cohort member, and so on until the series had been "averaged". Golden produced a single "average" tracing, representing a frontal and lateral view for each age group of both sexes. The published Bolton Standards (Broadbent et al. 1975) present two average tracings (frontal and lateral) for each age group, as the male and female average tracings were averaged together.

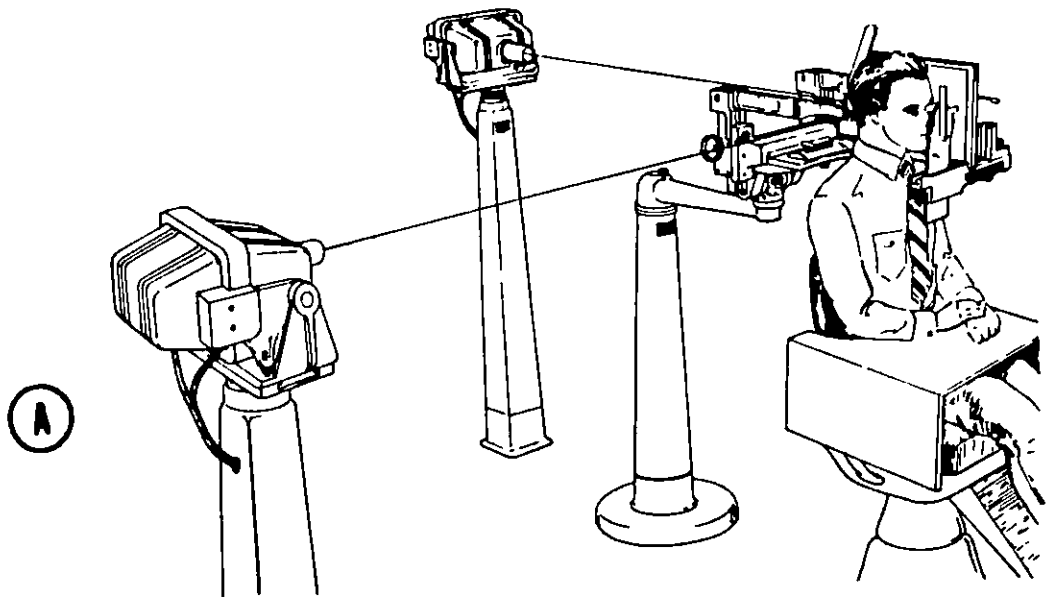
It should be noted that the frontal radiographs were not routinely taken during the first two years of age because of the difficulty of positioning the infant, coupled with the long exposure time then necessary to obtain radiographs. Thus, the frontal Bolton Standards extend from three years through eighteen years of age, whereas the lateral tracings begin at birth.

The radiographic images used for the published two dimensional Bolton tracings held their three-dimensional possibility latent until 1995 (Subramanyan, Dean 1996). Clearly, the Broadbent-Bolton cephalometer, when properly calibrated, not only provides a standardized means of

collecting head films, but also the basis for the collection of precisely co-registered biorthogonal films. Although the two films cannot be positioned at intersecting locations, recorded cephalometer-beam intersection point-to-film distances can correct for the offset. This correction is trivial assuming the beams of both x-ray sources orthogonally intersect in the center of the head. The specified distance from source to intersection point is five feet.

The Broadbent Orientator (Broadbent et al. 1975) presents a two-dimensional representation of the correspondence between points in the frontal and lateral radiographs. The spreading horizontal lines correct for magnifications inherent in the spread of the x-ray beam from two orthogonal single point sources (Figure 1) located five feet from the center of the head (Broadbent 1931; Grayson 1988). Regular use of the Broadbent Orientator for three-dimensional data collection was cumbersome without the aid of computers (Baumrind et al. 1983).

When introduced, the Broadbent roentegenographic cephalometer, was originally intended for use in longitudinal studies and as a diagnostic imager



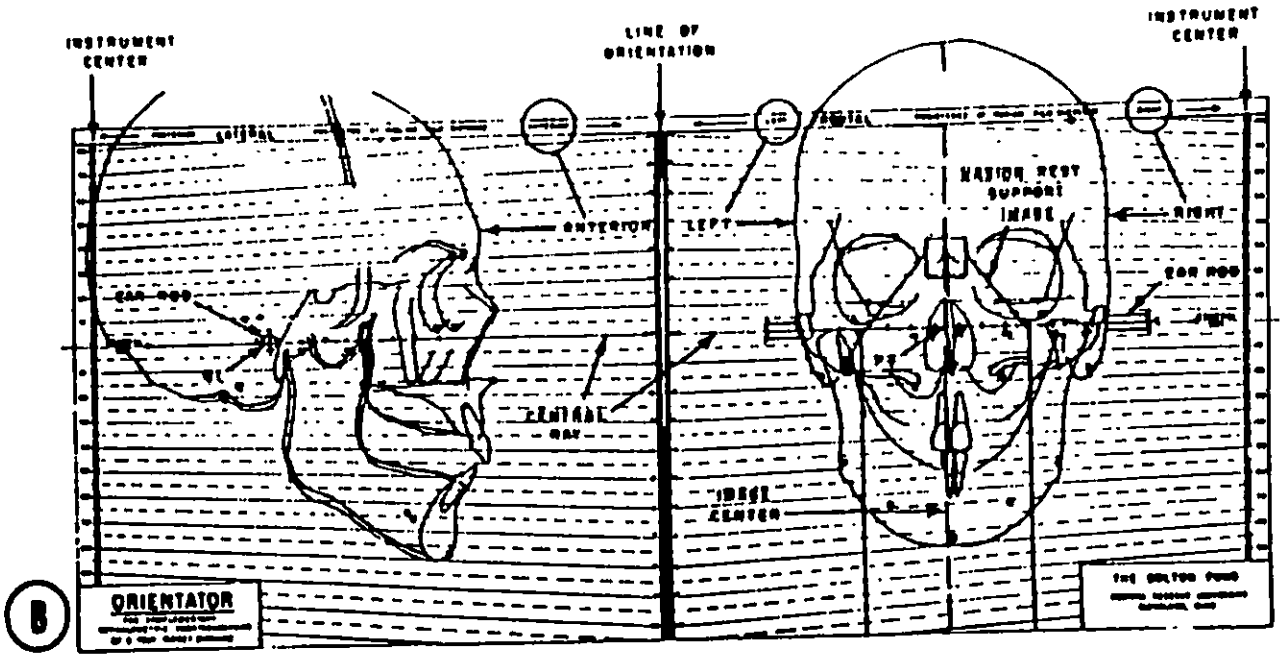


Figure 1. (A) Broadbent-Bolton Cephalometer
(B) Broadbent-Bolton Orientator
(Both illustrations © Bolton-Brush Growth Study Center, presented here with permission of the BBGSC).

(Broadbent 1931; Ricketts 1981). However, orthodontists and other craniofacial practitioners subsequently made little diagnostic use of frontal radiographs. The lateral film continues to be, primarily, a time-ordered record and an intrigal part of the usual diagnostic armamentarium.

Cephalometric research using lateral film tracings was most prolific between 1950 and 1985 (Blafer 1971; Ricketts 1972; Hixon 1972; Goldberg 1973; Binder 1979; Ricketts 1981; Mark et al. 1982). However, since the 1960's there has been moderate research interest in the use of the frontal film for asymmetry or three-dimensional studies (Baumrind, Frantz 1971; Sekiguchi, Savara 1972; Moyers et al. 1979; Vig 1982; Bookstein 1983; Adenwalla et al. 1988; Grayson et al. 1988; Major et al. 1994). It was soon noted that lack of consideration of frontal cephalograms risks missing the diagnosis of asymmetries, potentially resulting in treatment failures (Schmid et al. 1991; Melnik 1992).

The need for three-dimensional cephalometry was recognized in the 1960's by Savara (Savara 1965), and has been confirmed by many (Solow 1970; Hixon 1972; Goldberg 1973; Maganzini 1974; Ricketts 1981; Vig 1982; Baumrind

et al. 1983; Baumrind et al. 1983; Grayson 1989; Altobelli et al. 1993).

Altobelli, (1993) specifically called attention to the lack of three-dimensional standards for pediatric and adult craniofacial patients. Dean and colleagues (1997) has noted that these standards would be an important tool in the study of craniofacial variation, as well as diagnosis, treatment planning, stereotactic treatment, prosthetics designs, and outcome assessment.

Different techniques to abstract three dimensional coordinate data from biorthogonal head films, have been offered (Savara 1965; Bookstein 1982; Baumrind et al. 1983; Grayson et al. 1988; Bookstein et al. 1991; Spolyar et al. 1993; Motegi et al. 1996; Subramanyan and Dean 1996; Dean et al. 1997), but this work remains impractical because of hardware and software limitations, high-cost, and the time consuming nature of pencil tracing of films and mouse-based tracing feature identification from tracings.

The use of computer-readable digital films will likely have an important role in reinitiating three-dimensional cephalometrics. However, the importance of

computer-based cephalometry was long ago seen by Dr. R. M. Ricketts:

> "Cephalometrics, when computerized, becomes the most powerful tool of information yet devised for the practicing orthodontist" (Ricketts 1972).

It is unlikely that the use of frontal and lateral radiographs will be replaced by the use of CT-scan in Orthodontics, even though this modality provides an easier way of producing three-dimensional images (Bettega et al. 1996). 3D-CT scans are currently more expensive and its radiation exposure is higher than the required for a plain film roentgenographic cephalograms. For example, based on information of ten years ago, a pair of cephalograms involves approximately 26 mrad skin dose to the subject, whereas a three-dimensional CT scan would expose the subject to about 6.5 rad (Tyndall et al. 1988; Grayson et al. 1988). However, both these figures have likely gone down since.

Given the continued use of biplane radiographs, Dean and colleagues (Subramanyan, Dean 1996; Dean et al. 1997) have developed software, 3dCEPH, to collect three-dimensional coordinates directly from digital cephalogram images, eliminating the need for tracing and mouse-based

tables to digitize tracings. These images, in combination with 3D CT, may soon become a baseline for surgical patients. Together they provide the benefit of detailed pre-surgical images and the ability to track post-surgical progress of patients with frontal and lateral radiographs alone (Subramanyan, Dean 1996; Dean et al. 1997).

Using the 3dCEPH computer program sixteen of the female Bolton Faces have been digitized. After that all the participants' landmarks were averaged, within each age group. Each landmark's relocation for this group of 16 Bolton Faces was evaluated, biological year by year, using the procrustes algorithm (Rohlf 1988; Gower 1975). Because of the known sexual dimorphism that occurs during normal craniofacial growth (Broadbent et al. 1975; Ursi 1993), this work will be repeated separately for the correspondent male sample of sixteen Bolton Faces.

The three-dimensional Bolton Face age group averages here produced differ from the published average tracings (Broadbent et al. 1975) because:

1. In the original study male and female's Bolton Faces were averaged together.
2. The landmark coordinates in the present study were collected separately from each

female Bolton Face and mathematically averaged.

3. The current study includes separate collection of bilateral structures (i.e. right and left side landmarks were separately identified on frontal and lateral x-rays).

4. The 3dCEPH implementation of the Broadbent-Bolton Orientator allowed for correction of magnification due to the direction of the x-ray beam, and medio-lateral offset (ML distance) of the lateral film from the porionic axis, and posterior-anterior offset (P+ distance) of the frontal (postero-anterior) film from the porionic axis.

The Procrustes algorithm (Rohlf and Bookstein 1988) provides a mechanism for optimal superimposition of two sets of homologous landmarks on their shared centroid. The remaining mismatch between the two sets of landmarks provides size, orientation, and positional information. The advantages of this method over traditional cephalometric superimposition techniques are:

1. Size is treated as a separate variable and does not over-determine the result.

2. No landmark is seen as primary or stationary during the superimposition.

3. The result is presentable in diagrammatic form that looks like the original data rather than a column of numbers (distances).

Procrustes analysis has recently been recognized in clinical orthodontic studies (Singh et al. 1997) as a convenient way to study geometric relationships separately from previously confounding size differences.

In the discussion it is rank order the Procrustes distances of each landmark. It is then analyzed the translocation of specific groups of landmarks in procrustes distance units (PDU), and their level of participation in the overall shape modification that occurs between each pair of adjacent age groups. A single landmark cannot describe a biological feature. Thus, the use of landmark groups to describe craniofacial areas may prove to be clinically more useful. In addition to Procrustes distances, it is graphically displayed the orientation of landmark translocations in the discussion and compared the results achieved with what was previously published in the literature.

MATERIAL AND METHODS

The first step in this project was to capture three-dimensional landmarks from sixteen female Bolton Face image series. To do so the following steps were taken. First, sixteen female Bolton Face cephalogram series were scanned. Second, identification via computer-mouse of fifty cephalometric landmarks in each frontal and lateral film pair. Third, determining the average of all the three-dimensional landmarks found for each age group. All these steps were made possible through the use of a computer program, 3dCEPH, which was developed specifically for this purpose (Subramanyan, Dean 1996).

The sixteen female Bolton Faces used in this study identified by Bolton Identification Numbers: B0115, B0131, B0133, B1123, B1197, B1208, B1212, B1242, B2030, B2097, B2140, B2144, B2187, B2462, B2558 and B3037. Each of these Bolton Faces contributed with posteroanterior (frontal) and lateral plain film cephalograms annually, from ages three to eighteen. Because each individual missed one or more of their annual visits, a total of 186

frontal and lateral pairs (372 cephalograms) were available, out of the theoretical potential of 256 pairs (Appendix 1). This sample is more than adequate for the purpose of constructing a clinically relevant growth study.These images were then electronically scanned and digitized.

The following lists the steps in the use of the 3dCEPH program:

1. Align the frontal and lateral images from each visit. It is important to check if the head is facing the correct side in both images. The lateral image should be facing to the right. The frontal should display a shorter ear rod on the left.

2. 3dCEPH presents a computer graphic version of the Broadbent-Bolton Orientator. The Orientator assists the alignment of the frontal and lateral films. To align both images with landmarks identified by others, one identifies four fiducial points, which are punched holes applied prior to scanning. They form a preset rhomboid pattern. Both porion landmarks (in this case as the center of the ear rod) are identified on both images. Nasion (see Glossary for landmark definitions) is identified on the frontal only to assist in specifying the mid-sagittal plane. When the image orientation is completed, the P+ and ML distances are inserted. These distances determine the horizontal position of the images along the simulated x-ray beams (Figure 1). Vertical alignment of the frontal image is done by moving the image up or down so that the bi-porion (ear rod) axis ends up represented by a solid yellow horizontal line (the other

dotted horizontal orientator lines are displayed in red). Next, in the lateral view porion is located with the help of a size-variable circle. The center of the circle, only at this point, locates mechanical porion. To complete the vertical alignment of the lateral image, porion becomes the axis of rotation. The image is rotated until landmarks, which are identifiable in both views (i.e., menton, upper incisor edge, and supraorbital point), are put in best alignment using the horizontal orientator lines. The final check of lateral and frontal positioning is about the Frankfort plane (porion-infraorbitale). Finally nasion is re-checked in the frontal view. It must continue to lie in the midline and be vertically coordinated with nasion of the lateral view.

3. Once the images are aligned, the next step is landmark identification. The 3dCEPH software displays an estimated overlay of the same 50 landmarks on both the frontal and lateral views. Each landmark is manually nudged to its appropriate position. Sometimes a zoomed view is necessary. 22 of these landmarks can be accurately seen in only one of the image views, however the horizontal lines of the Broadbent-Bolton Orientator allow one to site the missing landmark across to the other image.

4. Following landmark identification the data is saved. Besides the xyz coordinate data collected, the Bolton Face's visit number, sex, date of birthday (day, month and year), date of visit (day, month and year), date of the user's digitization, name of the operator, and any possible remarks or observations are recorded.

In order to reduce inter-operator variability (Sekiguchi, Savara 1972; Moyers, Bookstein 1979; El Mangoury et al. 1987; Adenwalla et al. 1988; Major et al. 1994), I and several other workers at the Bolton-Brush Growth Study Center have attempted to write standard landmark definitions for three-dimensional biorthogonal plain film x-ray landmark identification (see Glossary). The initial definitions were based on Grayson's 3D landmark definitions (Grayson et al. 1988).

The data for the sixteen female, age cohorts, ages 3-18, was averaged. No attempt was made to fill-in missing data sets (i.e., data for missed visits to the Bolton Study). The averaged data for each landmark is in the form of Cartesian coordinates, x, y, and z.

The last objective of this study was to analyze changes in shape between the Bolton Face cohort, ages 3-18. Another computer program, SPLUS (Mathsoft Inc.) was used to calculate Procrustes distances between adjacent age groups of the sixteen sets of averaged landmarks.

RESULTS

The Procrustes algorithm was used to match adjacent sets of average landmarks. Overall Procrustes distance and Procrustes distance of each of the fifty landmarks studied were produced. The results are here presented by age groups. There are sixteen age groups, each one corresponding to a one-year period, thus fifteen comparisons.

In each report the landmarks are ranked in descendent order in Procrustes distance units (PDU). The highest ranked landmarks show the most shape change between the two average landmark sets. To the right of each Procrustes distance table there is the three-dimensional plot of each landmark pair represented in three different views (lateral, frontal and axial). Figure 2 provides a list of the landmarks used and a frame representation of these landmarks in three different views. The third one is not seen during landmark digitization in 3dCEPH, but is easy to produce thereafter.

1.	Sella
2.	Basion
3.	Condylion-R
4.	Condylion-L
5.	Mechanical Porion-R
6.	Mechanical Porion-L
7.	Nasion
8.	Supraorbital-R
9.	Supraorbital-L
10.	Medial Orbit-R
11.	Medial Orbit-L
12.	Lateral Orbit-R
13.	Lateral Orbit-L
14.	Orbitale-R
15.	Orbitale-L
16.	Piriform-R
17.	Piriform-L
18.	Anterior Nasal Spine
19.	Posterior Nasal Spine
20.	A Point
21.	Supradentale
22.	Upper Incisor Edge
23.	Upper First Molar Cusp-R
24.	Upper First Molar Cusp-L
25.	Lower Incisor Edge
26.	Infradentale
27.	Lower First Molar Cusp-R
28.	Lower First Molar Cusp-L
29.	B Point
30.	Pogonion
31.	Menton
32.	Gonion-R
33.	Gonion-L
34.	Lateral Condylar Pole-R
35.	Lateral Condylar Pole-L
36.	Central In Root Apex-R
37.	Central In Root Apex-L
38.	Ante Gonion -R
39.	Ante Gonion -L
40.	Opisthion
41.	Opisthocranion
42.	Inion
43.	Endinion
44.	Glabella
45.	Rhinion
46.	Mastoidale - R
47.	Mastoidale - L
48.	Euryon - R
49.	Euryon - L
50.	Vertex

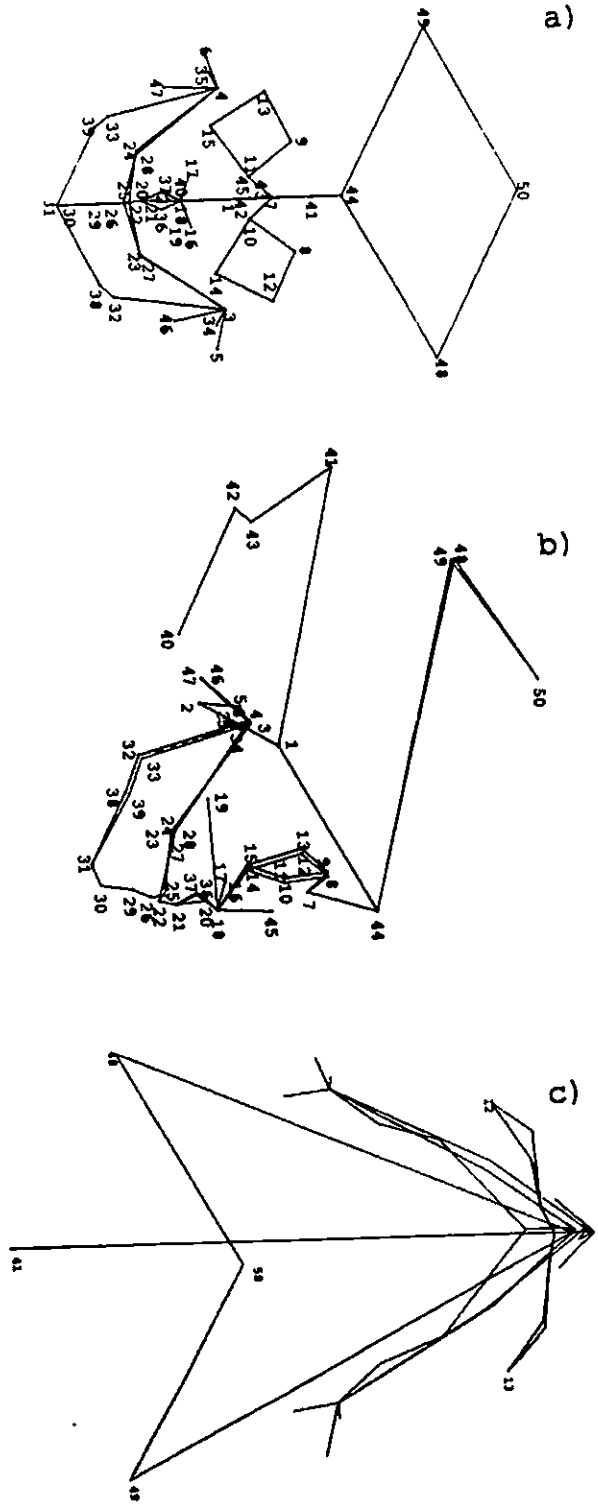


Figure 2. Three-Dimensional Landmarks labeled for the: a) frontal view, b) lateral view, and c) axial view. The landmark that correspond to the number are listed.

Rank	Landmark	PDU
1	50.Vertex	14.036
2	41.Opistho	13.454
3	42.Inion	10.630
4	43.Endinio	8.485
5	48.EuryonR	8.367
6	03.CondylR	7.874
7	46.Mast-R	7.874
8	47.Mast-L	7.681
9	44.Glabele	7.071
10	06.MecPorL	7.000
11	23.UppMC-R	7.000
12	49.EuryonL	6.782
13	04.CondylL	6.782
14	34.LatCP-R	6.708
15	24.UppMC-L	6.403
16	38.Agoni-R	6.403
17	39.AGoni-L	6.403
18	33.Gonio-L	6.403
19	40.Opisthi	6.325
20	36.CenRA-R	6.164
21	37.CenRA-L	6.083
22	32.Gonio-R	5.916
23	35.LatCP-L	5.477
24	16.Pirif-R	4.000
25	10.MedOrbR	3.464
26	02.Basion	3.162
27	25.LowerIE	3.162
28	30.Pogonio	3.162
29	19.PNSpine	3.000
30	31.Menton	3.000
31	11.MedOrbL	3.000
32	05.MecPorR	3.000
33	17.Pirif-L	3.000
34	14.Orbit-R	2.449
35	29.B-Point	2.236
36	18.ANSpine	2.236
37	27.LowMC-R	2.236
38	22.UpperIE	2.000
39	01.Sella	2.000
40	15.Orbit-L	1.732
41	13.LtrOrbL	1.414
42	09.SupOrbL	1.414
43	28.LowMC-L	1.414
44	45.Rhinion	1.414
45	20.A Point	1.414
46	21.Supdent	1.414
47	07.Nasion	1.414
48	08.SupOrbR	1.414
49	12.LtrOrbR	1.414
50	26.Infrade	1.000

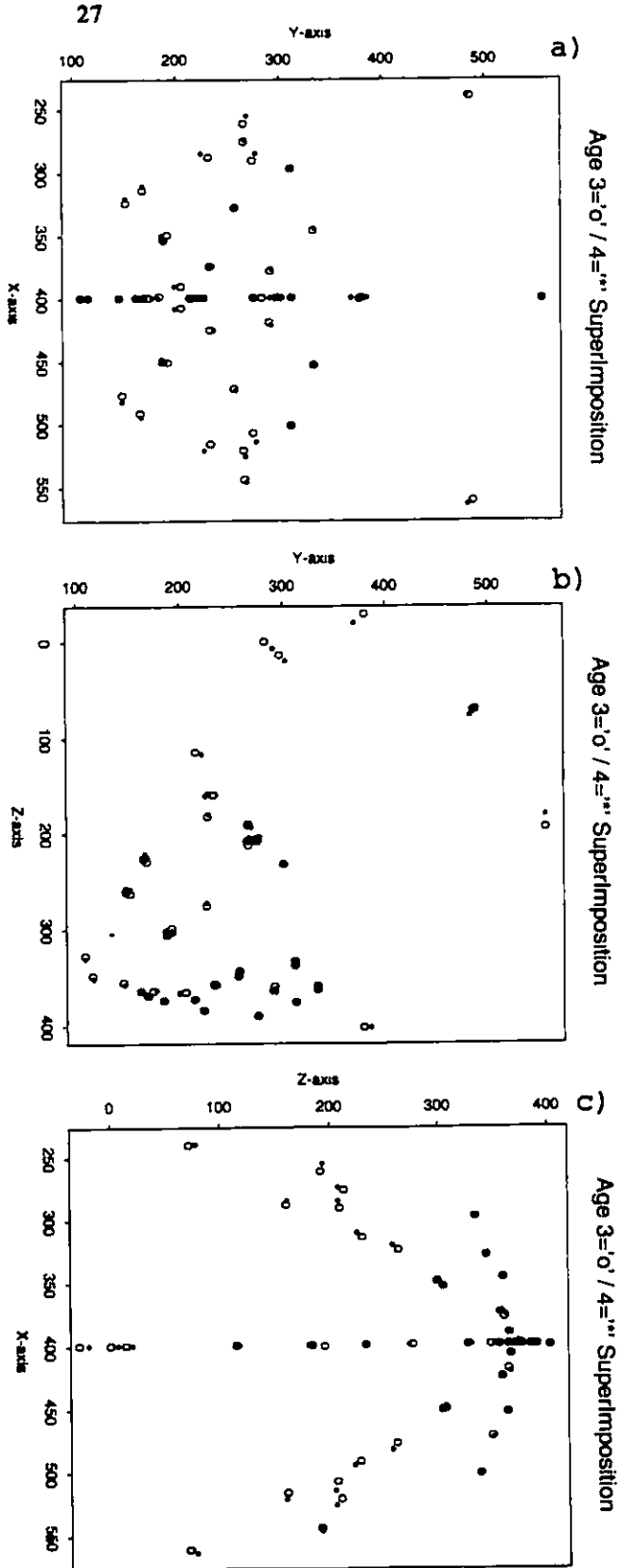


Figure 3. Procrustes Fit of landmarks from Age:3 to Age:4 in a) frontal view, b) lateral view, and c) axial view. Each landmark is ranked in a descendent order for shape modification.

Rank	Landmark	PDU
1	47.Mast-L	11.446
2	50.Vertex	11.225
3	46.Mast-R	8.544
4	40.Opisthi	8.062
5	10.MedOrbR	6.164
6	11.MedOrbL	5.916
7	32.Gonio-R	5.657
8	07.Nasion	5.099
9	03.CondylR	5.099
10	43.Endinio	5.000
11	04.CondylL	4.899
12	12.LtrOrbR	4.583
13	25.LowerIE	4.583
14	30.Pogonio	4.472
15	01.Sella	4.472
16	44.Glabele	4.472
17	24.UppMC-L	4.359
18	06.MecPorL	4.359
19	33.Gonio-L	4.359
20	42.Inion	4.243
21	28.LowMC-L	4.243
22	14.Orbit-R	4.123
23	23.UppMC-R	4.123
24	13.LtrOrbL	4.123
25	48.EuryonR	3.742
26	31.Menton	3.742
27	27.LowMC-R	3.606
28	34.LatCP-R	3.317
29	35.LatCP-L	3.317
30	38.AGoni-R	3.162
31	09.SupOrbL	3.162
32	29.B-Point	3.162
33	41.Opistho	3.000
34	08.SupOrbR	3.000
35	16.Pirif-R	2.828
36	21.Supdent	2.828
37	26.Infrade	2.449
38	05.MecPorR	2.449
39	15.Orbit-L	2.449
40	22.UpperIE	2.449
41	45.Rhinion	2.236
42	37.CenRA-L	2.236
43	17.Pirif-L	2.236
44	39.AGoni-L	2.236
45	49.EuryonL	2.236
46	36.CenRA-R	2.236
47	19.PNSpine	2.000
48	18.ANSpine	1.732
49	02.Basion	1.414
50	20.A Point	1.414

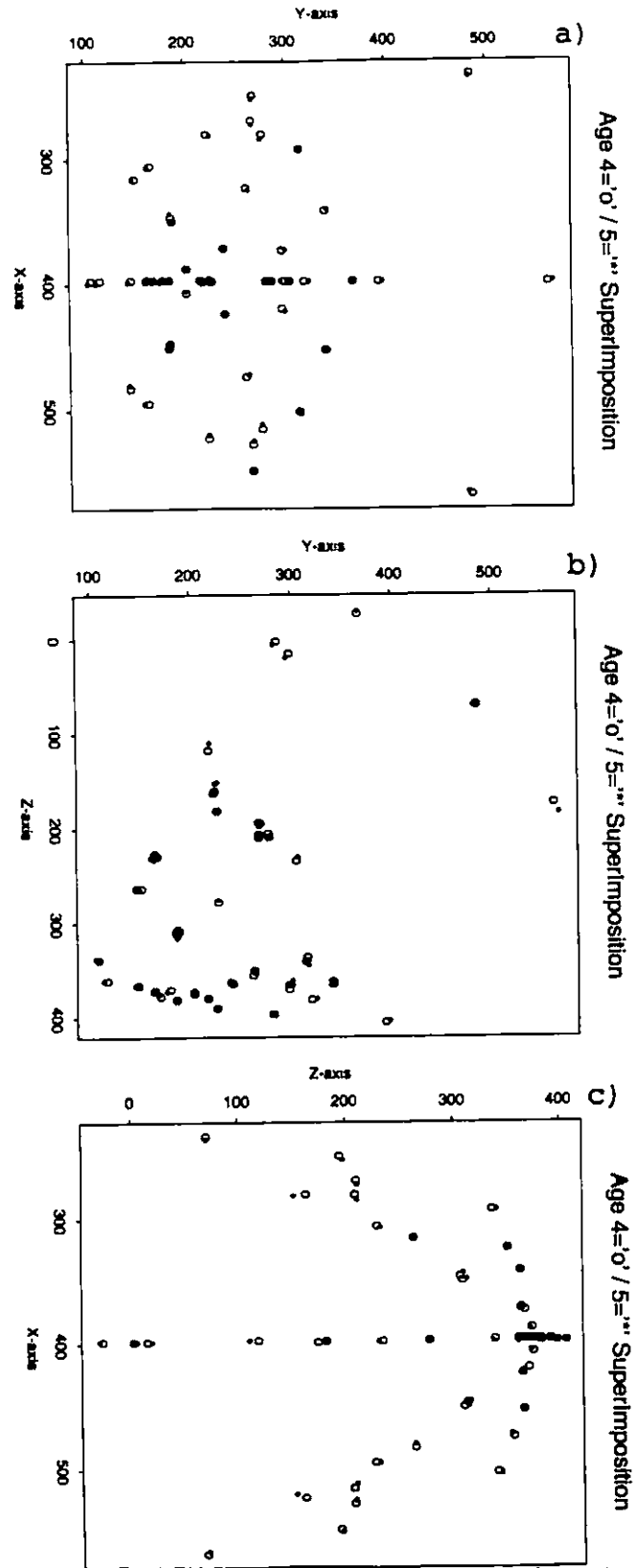


Figure 4. Procrustes Fit of landmarks from Age:4 to Age:5 in a) frontal view, b) lateral view, and c) axial view. Each landmark is ranked in a descendent order for shape modification.

Rank	Landmark	EDU
1	48.EuryonR	8.124
2	49.EuryonL	7.681
3	13.LtrOrbL	6.782
4	12.LtrOrbR	6.325
5	33.Gonio-L	5.099
6	36.CenRA-R	5.000
7	37.CenRA-L	4.472
8	08.SupOrbR	4.472
9	09.SupOrbL	4.472
10	40.Opisthi	4.243
11	45.Rhinion	4.243
12	27.LowMC-R	4.243
13	23.UppMC-R	4.243
14	32.Gonio-R	4.123
15	50.Vertex	4.123
16	28.LowMC-L	3.742
17	05.MecPorR	3.606
18	44.Glabele	3.606
19	04.CondylL	3.606
20	03.CondylR	3.317
21	02.Basion	3.162
22	42.Inion	3.162
23	29.B-Point	3.162
24	16.Pirif-R	3.162
25	01.Sella	3.162
26	24.UppMC-L	3.162
27	06.MecPorL	3.162
28	17.Pirif-L	3.000
29	39.AGoni-L	3.000
30	14.Orbit-R	3.000
31	10.MedOrbR	3.000
32	43.Endinio	3.000
33	47.Mast-L	2.828
34	19.PNSpine	2.828
35	46.Mast-R	2.449
36	30.Pogonio	2.449
37	31.Menton	2.449
38	22.UpperIE	2.449
39	18.ANSpine	2.449
40	26.Infrade	2.236
41	20.A Point	2.236
42	35.LatCP-L	2.236
43	15.Orbit-L	2.236
44	11.MedOrbL	1.732
45	38.AGoni-R	1.414
46	34.LatCP-R	1.414
47	21.Supdent	1.414
48	07.Nasion	1.000
49	25.LowerIE	1.000
50	41.Opistho	0.000

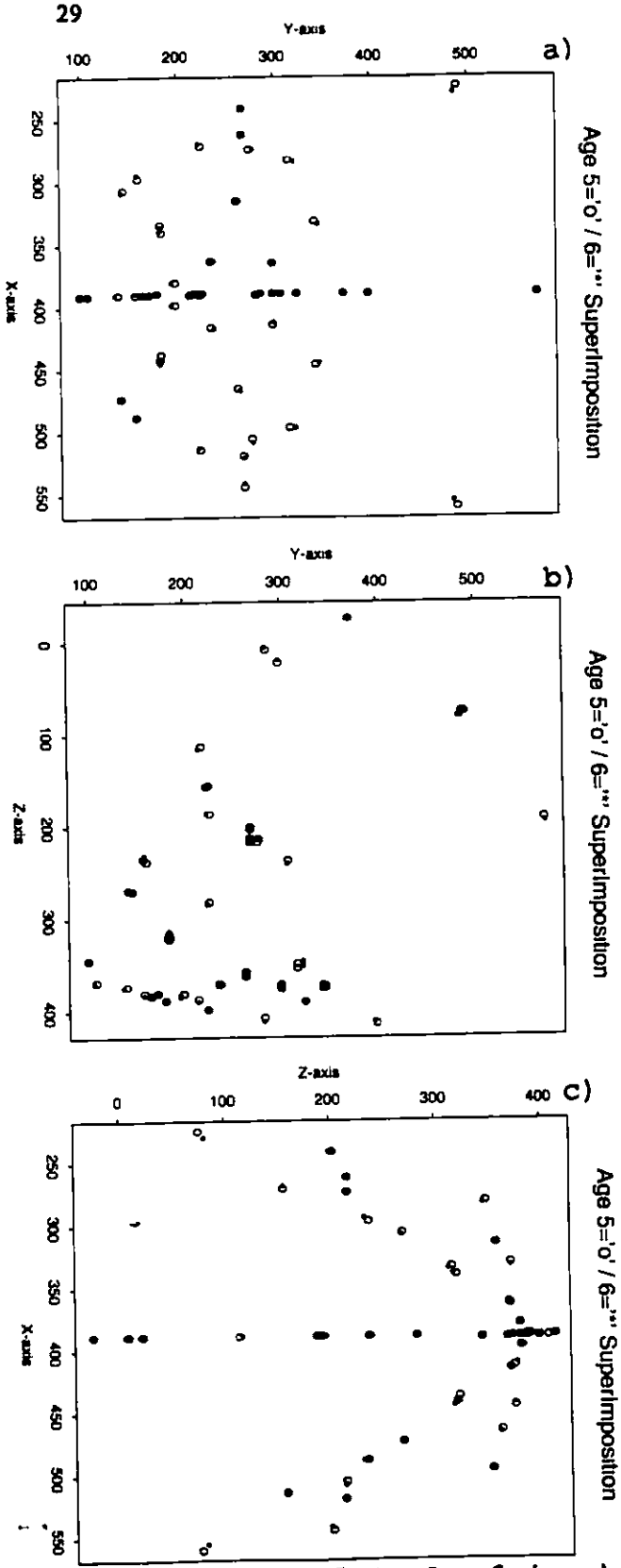


Figure 5. Procrustes Fit of landmarks from Age:5 to Age:6 in a) frontal view, b) lateral view, and c) axial view. Each landmark is ranked in a descendent order for shape modification.

Rank	Landmark	PDU
1	43.Endinio	7.616
2	28.LowMC-L	7.348
3	37.CenRA-L	6.782
4	42.Inion	6.708
5	27.LowMC-R	6.481
6	36.CenRA-R	6.403
7	24.UppMC-L	6.403
8	23.UppMC-R	5.657
9	40.Opisthi	5.099
10	17.Pirif-L	4.583
11	16.Pirif-R	4.583
12	31.Menton	4.472
13	35.LatCP-L	4.123
14	11.MedOrbL	4.123
15	44.Glabele	4.123
16	33.Gonio-L	3.742
17	48.EuryonR	3.742
18	49.EuryonL	3.742
19	05.MecPorR	3.606
20	07.Nasion	3.606
21	10.MedOrbR	3.606
22	22.UpperIE	3.317
23	01.Sella	3.162
24	04.CondylL	3.162
25	38.AGoni-R	3.162
26	50.Vertex	3.162
27	39.AGoni-L	3.000
28	21.Supdent	3.000
29	06.MecPorL	2.828
30	30.Pogonio	2.828
31	41.Opistho	2.828
32	46.Mast-R	2.449
33	08.SupOrbR	2.449
34	34.LatCP-R	2.449
35	32.Gonio-R	2.449
36	45.Rhinion	2.236
37	29.B-Point	2.236
38	14.Orbit-R	2.236
39	12.LtrOrbR	2.236
40	13.LtrOrbL	2.236
41	20.A Point	2.000
42	02.Basion	2.000
43	03.CondylR	1.732
44	26.Infrade	1.414
45	09.SupOrbL	1.414
46	47.Mast-L	1.000
47	19.PNSpine	1.000
48	15.Orbit-L	1.000
49	25.LowerIE	1.000
50	18.ANSpine	0.000

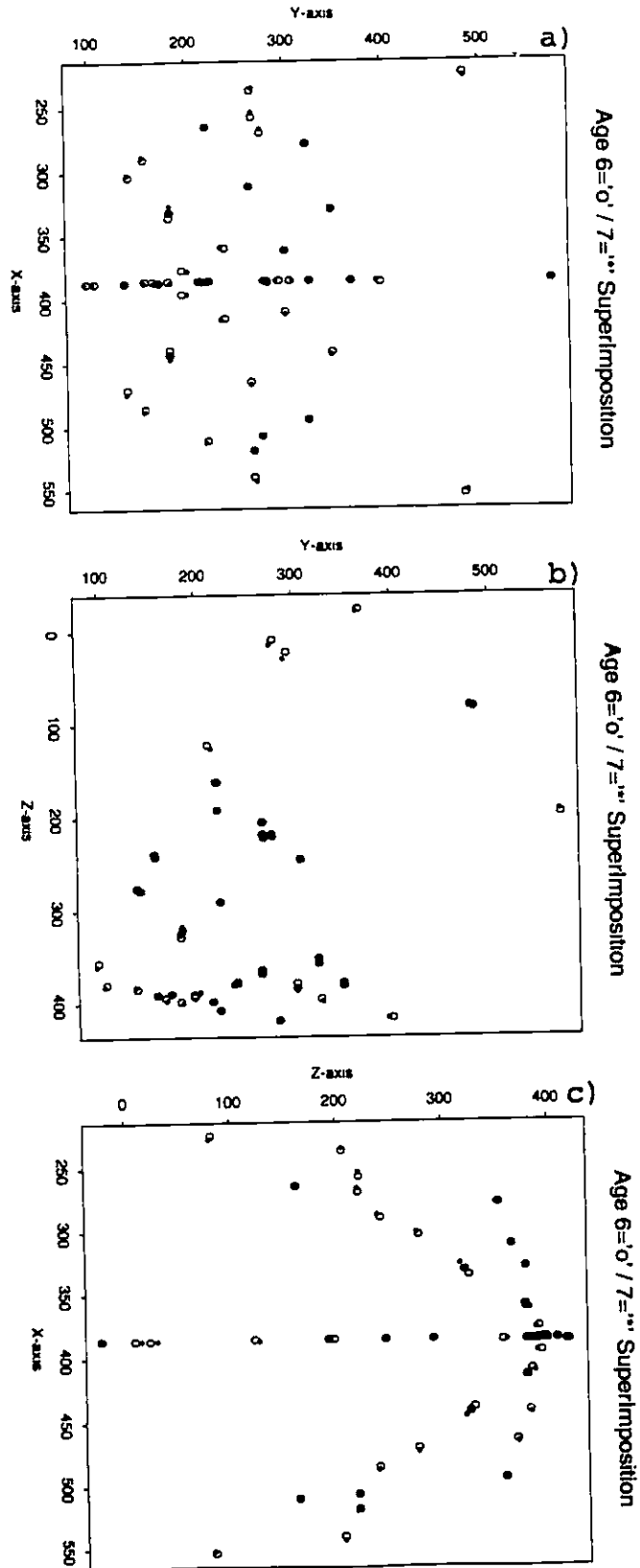


Figure 6. Procrustes Fit of landmarks from Age:6 to Age:7 in a) frontal view, b) lateral view, and c) axial view. Each landmark is ranked in a descendent order for shape modification.

Rank	Landmark	PDU
1	36.CenRA-R	11.225
2	37.CenRA-L	9.539
3	23.UppMC-R	9.055
4	24.UppMC-L	8.775
5	28.LowMC-L	8.307
6	27.LowMC-R	8.246
7	50.Vertex	7.000
8	43.Endinio	6.164
9	44.Glabele	5.831
10	05.MecPorR	5.745
11	22.UpperIE	5.657
12	21.Supdent	5.385
13	48.EuryonR	5.196
14	25.LowerIE	5.099
15	06.MecPorL	4.472
16	31.Menton	4.359
17	39.AGoni-L	4.123
18	38.AGoni-R	3.742
19	26.Infrade	3.606
20	40.Opisthi	3.606
21	49.EuryonL	3.464
22	42.Inion	3.317
23	45.Rhinion	3.162
24	12.LtrOrbR	3.162
25	02.Basion	3.162
26	08.SupOrbR	3.162
27	30.Pogonio	3.000
28	15.Orbit-L	3.000
29	34.LatCP-R	3.000
30	41.Opistho	2.449
31	46.Mast-R	2.449
32	14.Orbit-R	2.449
33	17.Pirif-L	2.449
34	33.Gonio-L	2.449
35	01.Sella	2.236
36	35.LatCP-L	2.236
37	07.Nasion	2.000
38	20.A Point	2.000
39	32.Gonio-R	2.000
40	29.B-Point	2.000
41	47.Mast-L	1.732
42	16.Pirif-R	1.732
43	03.CondylR	1.732
44	18.ANSpine	1.732
45	19.PNSpine	1.414
46	13.LtrOrbL	1.414
47	10.MedOrbR	1.414
48	04.CondylL	1.414
49	11.MedOrbL	1.000
50	09.SupOrbL	1.000

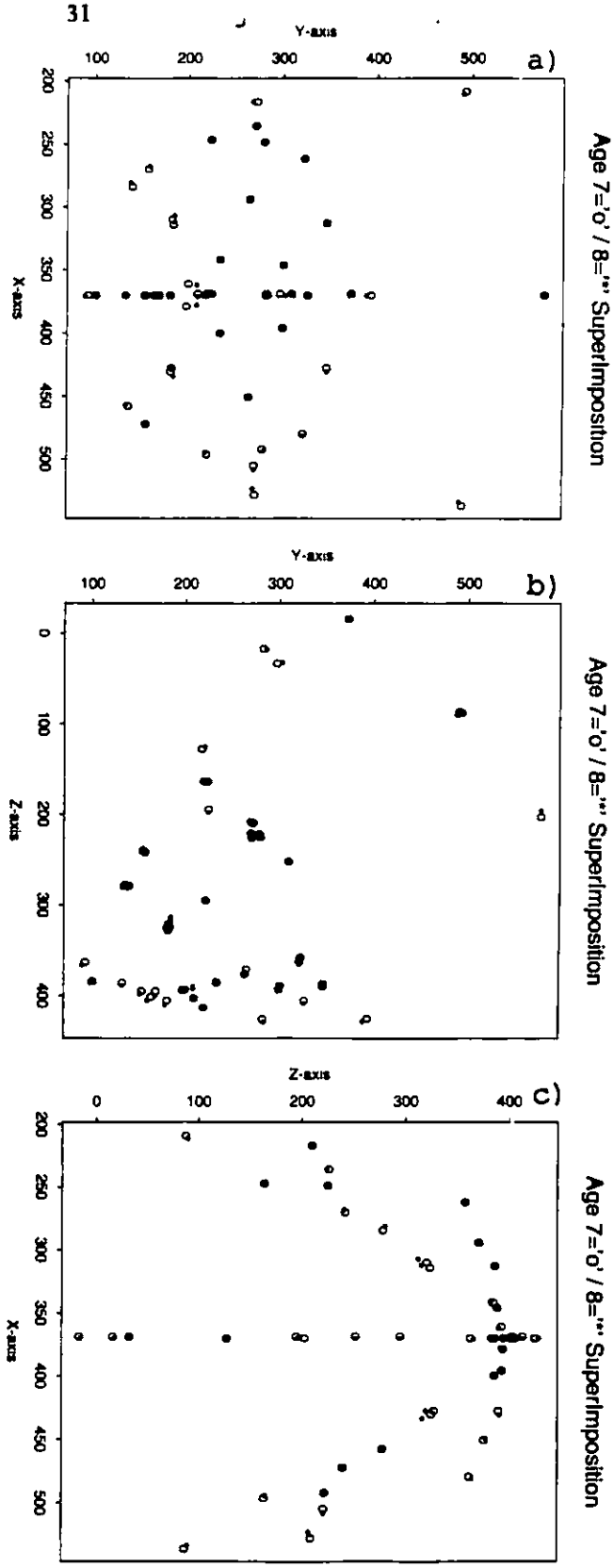


Figure 7. Procrustes Fit of landmarks from Age:7 to Age:8 in a) frontal view, b) lateral view, and c) axial view. Each landmark is ranked in a descendent order for shape modification.

Rank	Landmark	PDU
1	50.Vertex	8.062
2	44.Glabele	7.280
3	02.Basion	7.280
4	01.Sella	6.708
5	49.EuryonL	5.385
6	48.EuryonR	5.099
7	05.MecPorR	4.899
8	47.Mast-L	4.472
9	35.LatCP-L	4.243
10	34.LatCP-R	4.243
11	40.Opisthi	4.123
12	03.CondylR	3.742
13	32.Gonio-R	3.742
14	22.UpperIE	3.606
15	06.MecPorL	3.606
16	30.Pogonio	3.317
17	17.Pirif-L	3.162
18	33.Gonio-L	3.000
19	24.UppMC-L	3.000
20	12.LtrOrbR	3.000
21	14.Orbit-R	3.000
22	43.Endinio	3.000
23	15.Orbit-L	2.828
24	10.MedOrbR	2.828
25	42.Inion	2.828
26	08.SupOrbR	2.449
27	16.Pirif-R	2.236
28	04.CondylL	2.236
29	31.Menton	2.236
30	21.Supdent	2.236
31	13.LtrOrbL	2.236
32	38.AGoni-R	2.000
33	23.UppMC-R	2.000
34	41.Opistho	2.000
35	46.Mast-R	2.000
36	45.Rhinion	1.732
37	07.Nasion	1.732
38	36.CenRA-R	1.414
39	20.A Point	1.414
40	39.AGoni-L	1.414
41	09.SupOrbL	1.414
42	27.LowMC-R	1.414
43	28.LowMC-L	1.414
44	18.ANSpine	1.414
45	11.MedOrbL	1.000
46	29.B-Point	1.000
47	25.LowerIE	1.000
48	26.Infrade	1.000
49	37.CenRA-L	1.000
50	19.PNSpine	1.000

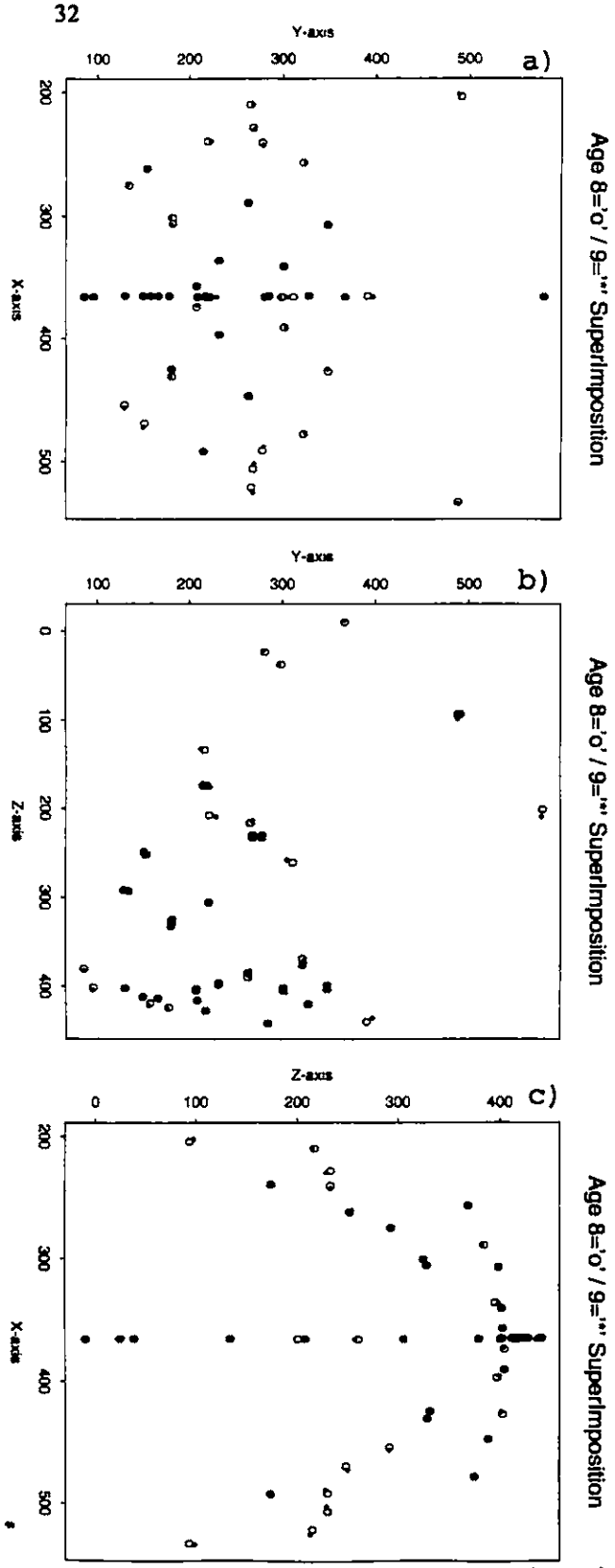


Figure 8. Procrustes Fit of landmarks from Age:8 to Age:9 in a) frontal view, b) lateral view, and c) axial view. Each landmark is ranked in a descendent order for shape modification.

Rank	Landmark	PDU
1	01.Sella	8.544
2	02.Basion	7.874
3	48.EuryonR	7.141
4	49.EuryonL	7.071
5	46.Mast-R	6.403
6	50.Vertex	6.000
7	34.LatCP-R	5.196
8	35.LatCP-L	5.099
9	38.AGoni-R	4.583
10	42.Inion	4.583
11	40.Opisthi	4.243
12	39.AGoni-L	4.243
13	24.UppMC-L	4.123
14	15.Orbit-L	3.606
15	47.Mast-L	3.317
16	10.MedOrbR	3.317
17	43.Endinio	3.317
18	04.CondylL	3.317
19	45.Rhinion	3.162
20	28.LowMC-L	3.000
21	03.CondylR	3.000
22	33.Gonio-L	2.828
23	23.UppMC-R	2.828
24	32.Gonio-R	2.449
25	27.LowMC-R	2.449
26	25.LowerIE	2.449
27	08.SupOrbR	2.236
28	41.Opistho	2.236
29	37.CenRA-L	2.236
30	11.MedOrbL	2.236
31	13.LtrOrbL	2.236
32	36.CenRA-R	2.000
33	44.Glabele	2.000
34	06.MecPorL	1.732
35	14.Orbit-R	1.732
36	09.SupOrbL	1.732
37	17.Pirif-L	1.414
38	22.UpperIE	1.414
39	26.Infrade	1.414
40	05.MecPorR	1.414
41	29.B-Point	1.000
42	12.LtrOrbR	1.000
43	20.A Point	1.000
44	07.Nasion	1.000
45	19.PNSpine	0.000
46	16.Pirif-R	0.000
47	21.Supdent	0.000
48	30.Pogonio	0.000
49	31.Menton	0.000
50	18.ANSpine	0.000

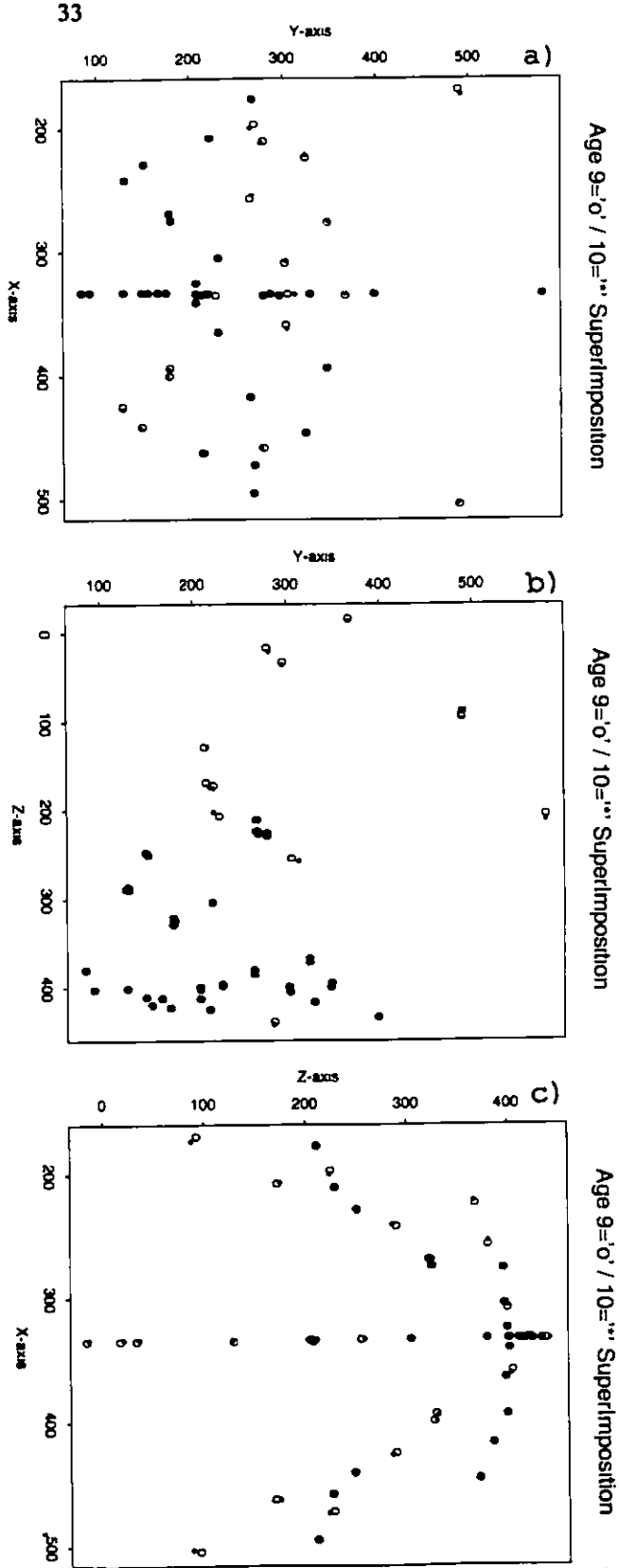


Figure 9. Procrustes Fit of landmarks from Age:9 to Age:10 in a) frontal view, b) lateral view, and c) axial view. Each landmark is ranked in a descendent order for shape modification.

Rank	Landmark	PDU
1	50.Vertex	10.100
2	47.Mast-L	8.944
3	48.EuryonR	7.000
4	46.Mast-R	6.708
5	43.Endinio	6.481
6	35.LatCP-L	6.000
7	49.EuryonL	5.831
8	38.AGoni-R	5.000
9	04.CondylL	4.690
10	39.AGoni-L	4.123
11	02.Basion	3.742
12	42.Inion	3.317
13	28.LowMC-L	3.162
14	31.Menton	3.000
15	34.LatCP-R	3.000
16	27.LowMC-R	3.000
17	14.Orbit-R	3.000
18	41.Opistho	2.449
19	30.Pogonio	2.449
20	08.SupOrbR	2.449
21	40.Opisthi	2.449
22	06.MecPorL	2.236
23	15.Orbit-L	2.236
24	18.ANSpine	2.236
25	20.A Point	2.236
26	03.CondylR	2.236
27	10.MedOrbR	2.236
28	11.MedOrbL	2.236
29	44.Glabele	2.000
30	05.MecPorR	2.000
31	01.Sella	1.732
32	23.UppMC-R	1.732
33	24.UppMC-L	1.732
34	16.Pirif-R	1.414
35	33.Gonio-L	1.414
36	17.Pirif-L	1.414
37	25.LowerIE	1.414
38	09.SupOrbL	1.414
39	12.LtrOrbR	1.414
40	29.B-Point	1.414
41	21.Supdent	1.414
42	19.PNSpine	1.000
43	13.LtrOrbL	1.000
44	36.CenRA-R	1.000
45	45.Rhinion	1.000
46	37.CenRA-L	1.000
47	07.Nasion	1.000
48	26.Infrade	1.000
49	32.Gonio-R	1.000
50	22.UpperIE	1.000

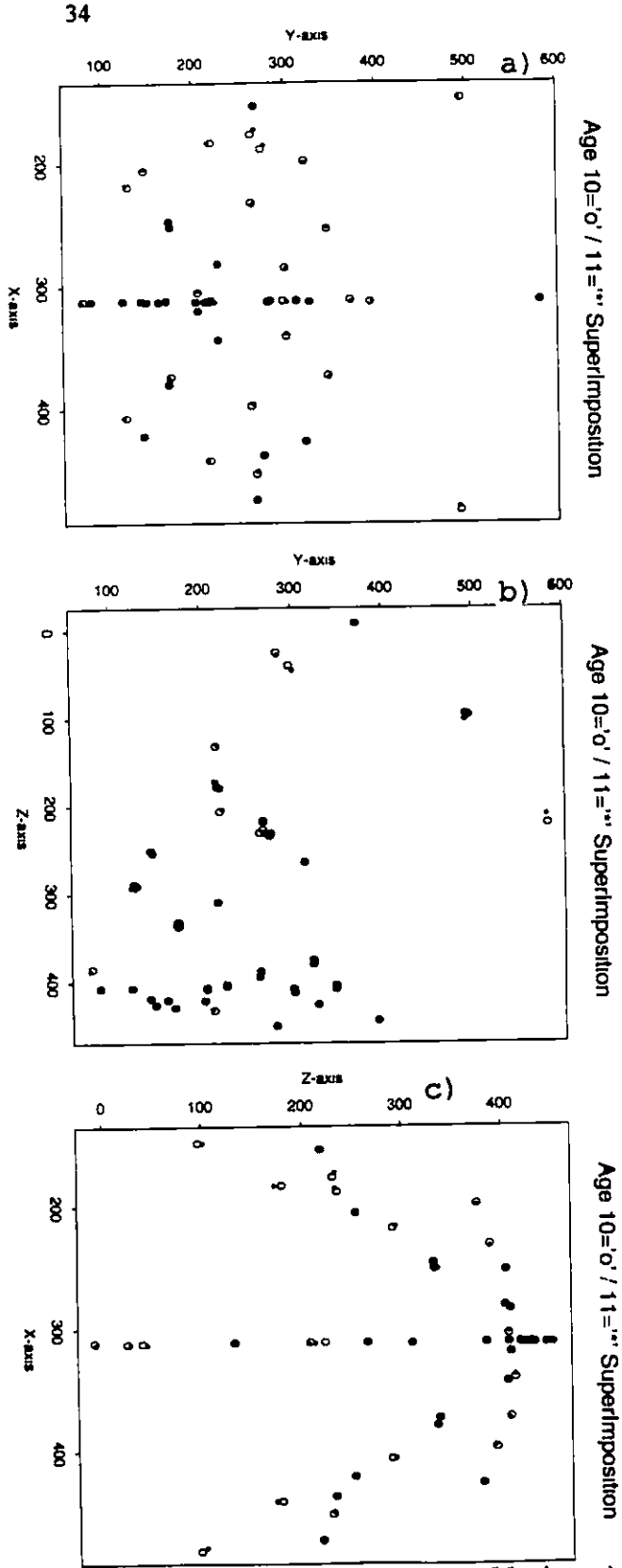


Figure 10. Procrustes Fit of landmarks from Age:10 to Age:11 in a) frontal view, b) lateral view, and c) axial view. Each landmark is ranked in a descendent order for shape modification.

Rank	Landmark	PDU
1	03.CondylR	5.099
2	24.UppMC-L	4.583
3	28.LowMC-L	4.359
4	23.UppMC-R	4.123
5	35.LatCP-L	4.123
6	04.CondylL	4.000
7	31.Menton	3.606
8	34.LatCP-R	3.606
9	05.MecPorR	3.606
10	40.Opisthi	3.606
11	39.AGoni-L	3.317
12	06.MecPorL	3.162
13	50.Vertex	3.162
14	14.Orbit-R	3.000
15	38.AGoni-R	3.000
16	30.Pogonio	3.000
17	17.Pirif-L	3.000
18	46.Mast-R	3.000
19	48.EuryonR	3.000
20	27.LowMC-R	3.000
21	26.Infrade	2.449
22	49.EuryonL	2.449
23	47.Mast-L	2.449
24	21.Supdent	2.236
25	41.Opistho	2.236
26	44.Glabele	2.236
27	32.Gonio-R	2.236
28	09.SupOrbL	2.236
29	12.LtrOrbR	2.236
30	29.B-Point	2.236
31	25.LowerIE	2.236
32	01.Sella	2.000
33	43.Endinio	2.000
34	18.ANSpine	2.000
35	16.Pirif-R	2.000
36	13.LtrOrbL	1.732
37	08.SupOrbR	1.732
38	15.Orbit-L	1.732
39	33.Gonio-L	1.414
40	42.Inion	1.414
41	02.Basion	1.414
42	07.Nasion	1.414
43	45.Rhinion	1.414
44	36.CenRA-R	1.414
45	37.CenRA-L	1.414
46	10.MedOrbR	1.414
47	11.MedOrbL	1.414
48	22.UpperIE	1.414
49	19.PNSpine	1.000
50	20.A Point	0.000

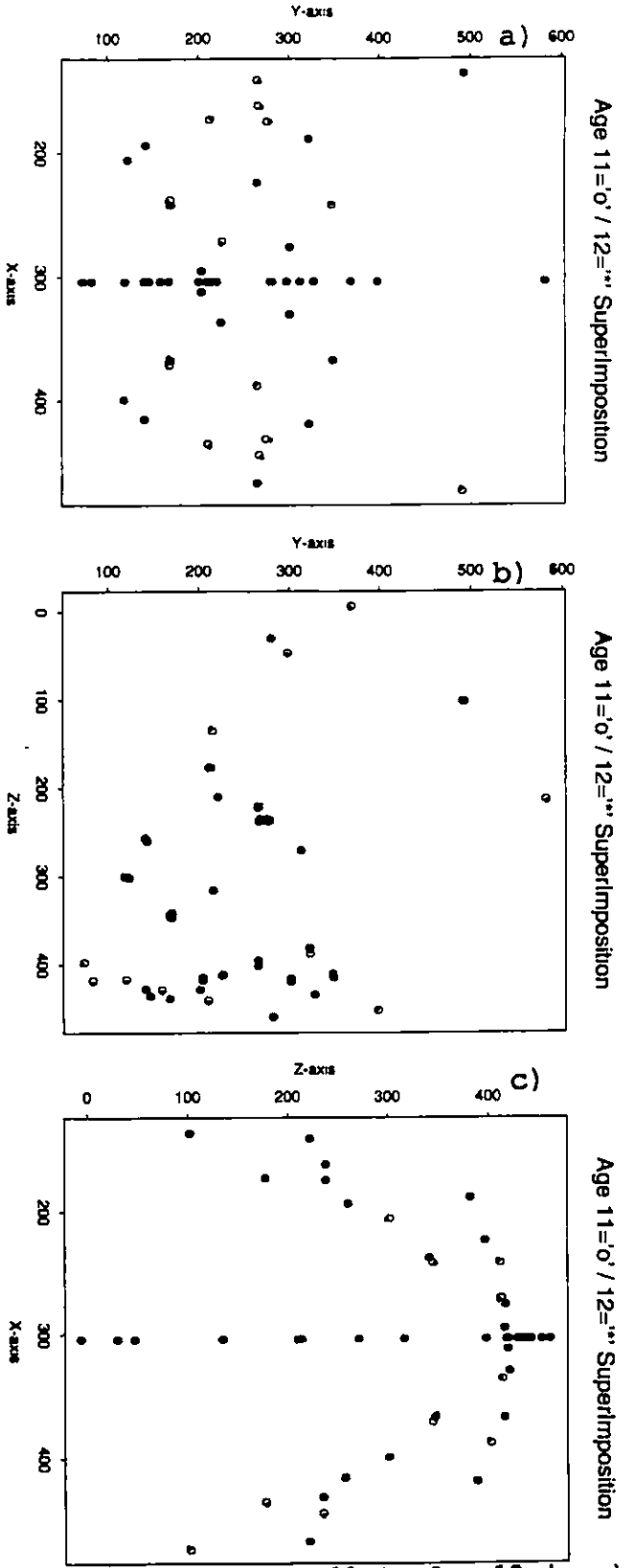


Figure 11. Procrustes Fit of landmarks from Age:11 to Age:12 in a) frontal view, b) lateral view, and c) axial view. Each landmark is ranked in a descendent order for shape modification.

Rank	Landmark	Distance
1	40.Opisthi	8.124
2	43.Endinio	5.477
3	42.Inion	5.196
4	49.EuryonL	5.099
5	32.Gonio-R	4.472
6	02.Basion	4.359
7	06.MecPorL	3.742
8	04.CondylL	3.606
9	33.Gonio-L	3.606
10	21.Supdent	3.317
11	18.ANSpine	3.162
12	47.Mast-L	3.162
13	01.Sella	3.162
14	15.Orbit-L	3.000
15	35.LatCP-L	2.828
16	46.Mast-R	2.828
17	14.Orbit-R	2.828
18	16.Pirif-R	2.828
19	34.LatCP-R	2.449
20	45.Rhinion	2.449
21	30.Pogonio	2.449
22	09.SupOrbL	2.449
23	48.EuryonR	2.449
24	27.LowMC-R	2.449
25	50.Vertex	2.449
26	08.SupOrbR	2.236
27	23.UppMC-R	2.236
28	24.UppMC-L	2.236
29	17.Pirif-L	2.236
30	36.CenRA-R	2.236
31	37.CenRA-L	2.236
32	03.CondylR	2.236
33	41.Opistho	2.236
34	28.LowMC-L	2.000
35	05.MecPorR	1.732
36	31.Menton	1.732
37	38.AGoni-R	1.732
38	44.Glabele	1.732
39	26.Infrade	1.732
40	11.MedOrbL	1.414
41	25.LowerIE	1.414
42	12.LtrOrbR	1.414
43	13.LtrOrbL	1.414
44	19.PNSpine	1.414
45	20.A Point	1.414
46	39.AGoni-L	1.414
47	07.Nasion	1.414
48	10.MedOrbR	1.414
49	29.B-Point	1.000
50	22.UpperIE	1.000

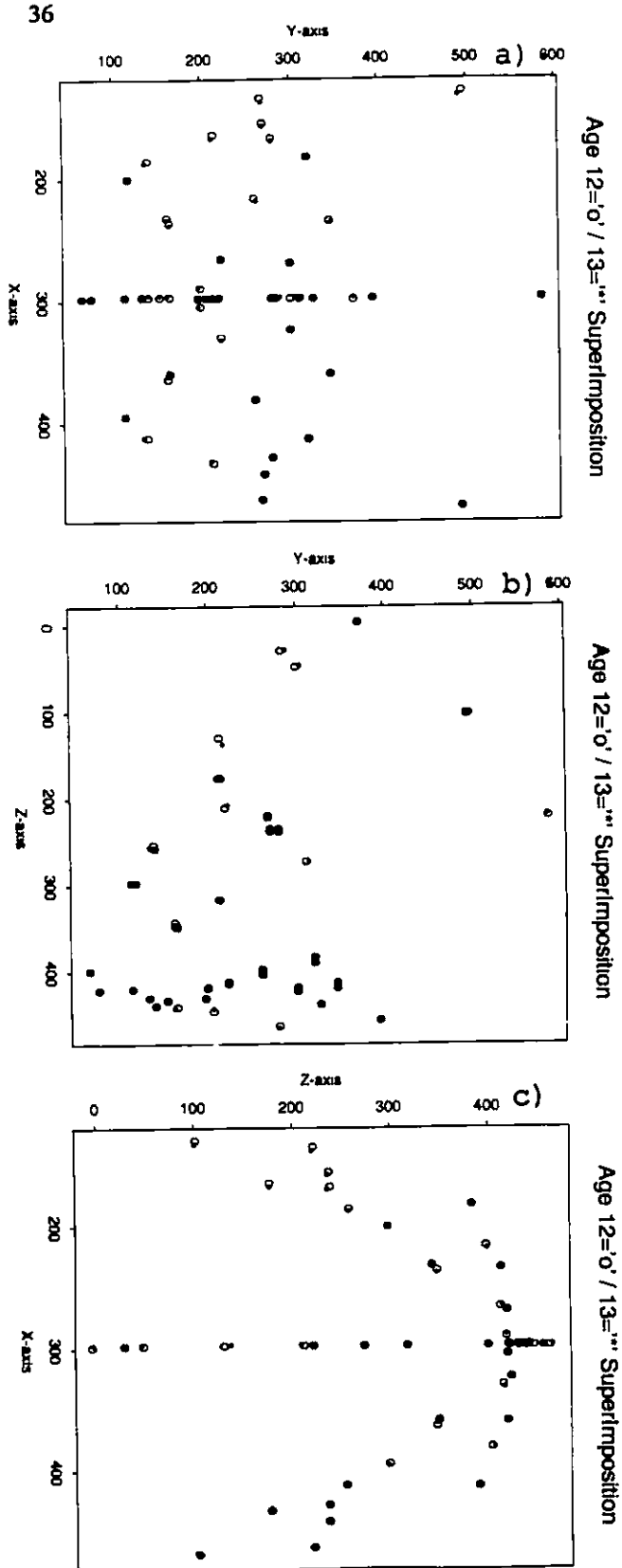


Figure 12. Procrustes Fit of landmarks from Age:12 to Age:13 in a) frontal view, b) lateral view, and c) axial view. Each landmark is ranked in a descendent order for shape modification.

Rank	Landmark	PDU
1	44.Glabele	13.038
2	40.Opisthi	7.348
3	10.MedOrbR	5.099
4	11.MedOrbL	5.099
5	03.CondylR	4.123
6	36.CenRA-R	3.742
7	38.AGoni-R	3.742
8	24.UppMC-L	3.742
9	28.LowMC-L	3.742
10	37.CenRA-L	3.606
11	16.Pirif-R	3.317
12	39.AGoni-L	3.162
13	31.Menton	3.162
14	41.Opistho	3.162
15	12.LtrOrbR	3.162
16	45.Rhinion	3.162
17	46.Mast-R	3.162
18	50.Vertex	3.162
19	26.Infrade	3.000
20	33.Gonio-L	3.000
21	13.LtrOrbL	3.000
22	27.LowMC-R	2.828
23	18.ANSpine	2.828
24	25.LowerIE	2.449
25	43.Endinio	2.449
26	32.Gonio-R	2.449
27	02.Basion	2.449
28	34.LatCP-R	2.449
29	35.LatCP-L	2.449
30	23.UppMC-R	2.236
31	01.Sella	2.236
32	42.Inion	2.236
33	47.Mast-L	2.236
34	49.EuryonL	2.236
35	21.Supdent	2.236
36	30.Pogonio	2.000
37	17.Pirif-L	2.000
38	07.Nasion	2.000
39	04.CondylL	2.000
40	48.EuryonR	1.732
41	19.PNSpine	1.732
42	14.Orbit-R	1.732
43	06.MecPorL	1.414
44	08.SupOrbR	1.414
45	15.Orbit-L	1.414
46	20.A Point	1.414
47	09.SupOrbL	1.414
48	22.UpperIE	1.414
49	29.B-Point	1.414
50	05.MecPorR	0.000

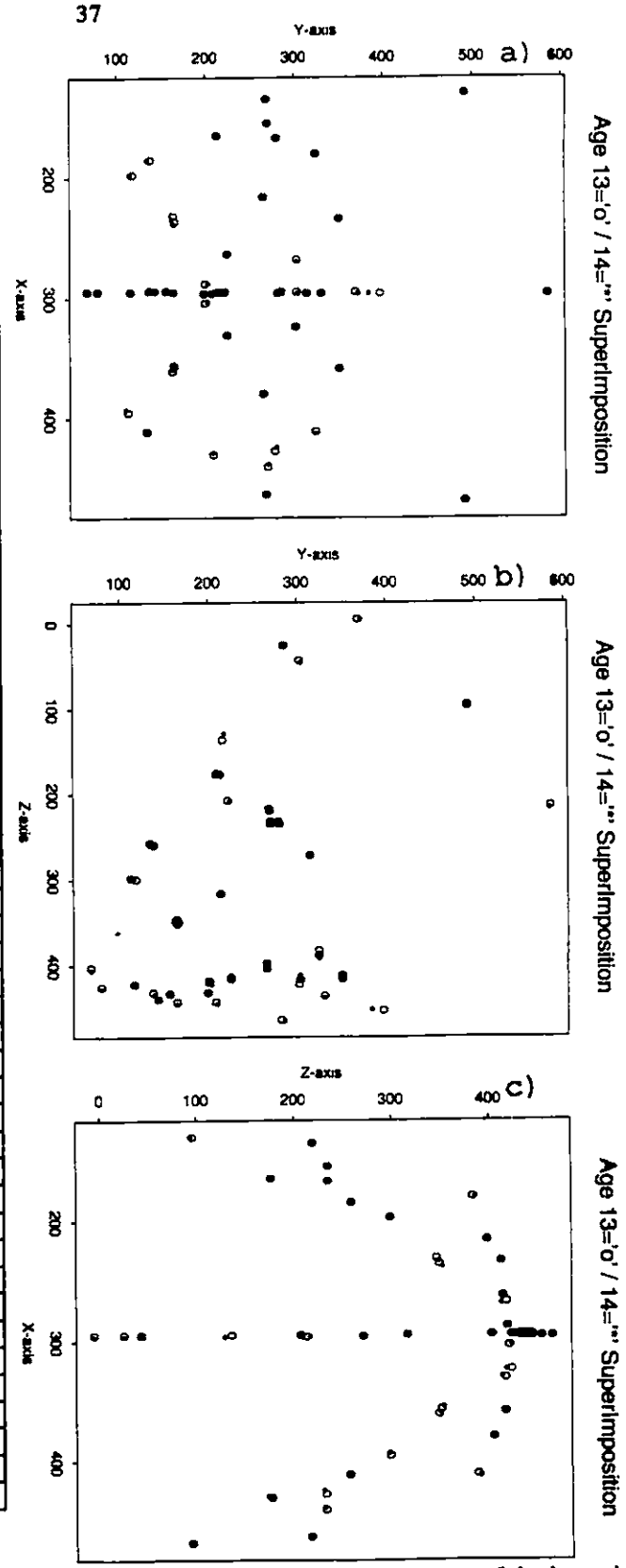


Figure 13. Procrustes Fit of landmarks from Age:13 to Age:14 in a) frontal view, b) lateral view, and c) axial view. Each landmark is ranked in a descendent order for shape modification.

Rank	Landmark	PDU
1	44.Glabele	14.177
2	40.Opisthi	6.403
3	12.LtrOrbR	5.385
4	13.LtrOrbL	5.000
5	10.MedOrbR	4.690
6	46.Mast-R	4.583
7	28.LowMC-L	4.359
8	11.MedOrbL	4.359
9	48.EuryonR	4.359
10	15.Orbit-L	4.243
11	31.Menton	4.243
12	47.Mast-L	4.123
13	06.MecPorL	4.123
14	49.EuryonL	4.123
15	05.MecPorR	3.742
16	37.CenRA-L	3.742
17	50.Vertex	3.742
18	04.CondylL	3.606
19	23.UppMC-R	3.606
20	34.LatCP-R	3.606
21	36.CenRA-R	3.606
22	25.LowerIE	3.606
23	27.LowMC-R	3.606
24	26.Infrade	3.317
25	07.Nasion	3.162
26	35.LatCP-L	3.162
27	14.Orbit-R	3.162
28	01.Sella	3.162
29	38.AGoni-R	3.162
30	32.Gonio-R	3.162
31	08.SupOrbR	3.000
32	03.CondylR	3.000
33	30.Pogonio	2.449
34	39.AGoni-L	2.449
35	33.Gonio-L	2.449
36	43.Endinio	2.236
37	20.A Point	2.236
38	02.Basion	2.236
39	24.UppMC-L	2.236
40	09.SupOrbL	2.236
41	17.Pirif-L	2.236
42	19.PNSpine	2.236
43	18.ANSpine	2.000
44	21.Supdent	2.000
45	45.Rhinion	1.732
46	29.B-Point	1.732
47	16.Pirif-R	1.732
48	42.Inion	1.000
49	22.UpperIE	1.000
50	41.Opistho	1.000

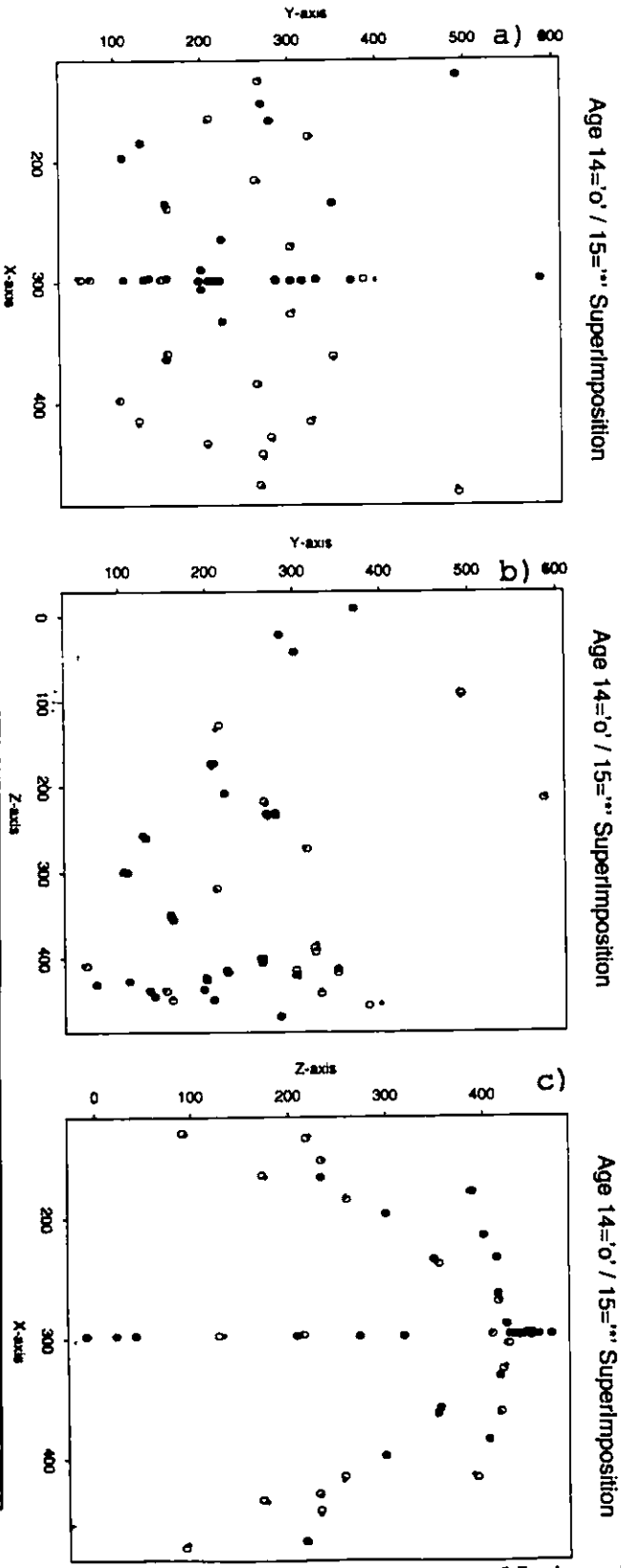


Figure 14. Procrustes Fit of landmarks from Age:14 to Age:15 in a) frontal view, b) lateral view, and c) axial view. Each landmark is ranked in a descendent order for shape modification.

Rank	Landmark	PDU
1	44.Glabele	12.083
2	50.Vertex	5.916
3	40.Opisthi	5.099
4	19.PNSpine	4.472
5	12.LtrOrbR	4.359
6	41.Opistho	4.243
7	43.Endinio	4.123
8	01.Sella	4.123
9	06.MecPorL	4.123
10	46.Mast-R	3.742
11	04.CondylL	3.742
12	08.SupOrbR	3.317
13	42.Inion	3.317
14	38.AGoni-R	3.000
15	15.Orbit-L	3.000
16	03.CondylR	3.000
17	48.EuryonR	3.000
18	34.LatCP-R	3.000
19	09.SupOrbL	2.828
20	23.UppMC-R	2.828
21	10.MedOrbR	2.828
22	17.Pirif-L	2.828
23	14.Orbit-R	2.449
24	47.Mast-L	2.449
25	27.LowMC-R	2.236
26	18.ANSpine	2.236
27	35.LatCP-L	2.236
28	16.Pirif-R	2.236
29	39.AGoni-L	2.236
30	07.Nasion	2.236
31	25.LowerIE	2.236
32	20.A Point	2.000
33	45.Rhinion	2.000
34	28.LowMC-L	2.000
35	02.Basion	1.732
36	49.EuryonL	1.732
37	37.CenRA-L	1.732
38	24.UppMC-L	1.414
39	11.MedOrbL	1.414
40	22.UpperIE	1.414
41	13.LtrOrbL	1.414
42	30.Pogonio	1.414
43	31.Menton	1.414
44	32.Gonio-R	1.414
45	33.Gonio-L	1.414
46	21.Supdent	1.000
47	36.CenRA-R	1.000
48	26.Infrade	1.000
49	05.MecPorR	1.000
50	29.B-Point	0.000

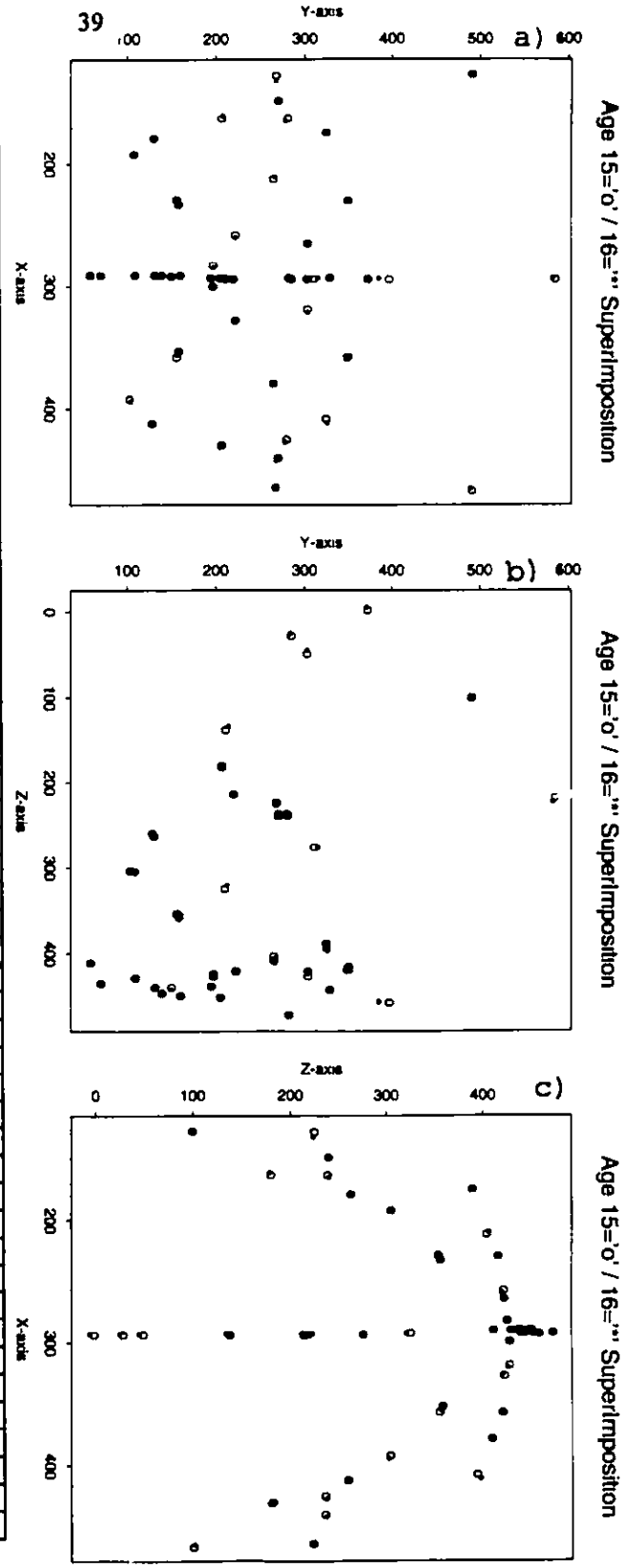


Figure 15. Procrustes Fit of landmarks from Age:15 to Age:16 in a) frontal view, b) lateral view, and c) axial view. Each landmark is ranked in a descendent order for shape modification.

Rank	Landmark	PDU
1	43.Endinio	7.280
2	50.Vertex	6.782
3	38.AGoni-R	6.708
4	42.Inion	5.916
5	41.Opistho	5.196
6	39.AGoni-L	4.359
7	06.MecPorL	4.243
8	12.LtrOrbR	4.123
9	13.LtrOrbL	4.123
10	14.Orbit-R	3.742
11	48.EuryonR	3.742
12	35.LatCP-L	3.742
13	03.CondylR	3.317
14	15.Orbit-L	3.162
15	34.LatCP-R	3.162
16	37.CenRA-L	3.000
17	33.Gonio-L	2.828
18	49.EuryonL	2.449
19	10.MedOrbR	2.449
20	20.A Point	2.236
21	44.Glabele	2.236
22	47.Mast-L	2.236
23	30.Pogonio	2.236
24	36.CenRA-R	2.236
25	05.MecPorR	2.236
26	40.Opisthi	2.000
27	32.Gonio-R	2.000
28	11.MedOrbL	2.000
29	27.LowMC-R	1.732
30	46.Mast-R	1.732
31	29.B-Point	1.732
32	04.CondylL	1.732
33	23.UppMC-R	1.732
34	26.Infrade	1.732
35	25.LowerIE	1.414
36	16.Pirif-R	1.414
37	17.Pirif-L	1.414
38	01.Sella	1.414
39	09.SupOrbL	1.414
40	31.Menton	1.414
41	45.Rhinion	1.000
42	24.UppMC-L	1.000
43	08.SupOrbR	1.000
44	02.Basion	1.000
45	22.UpperIE	1.000
46	07.Nasion	1.000
47	21.Supdent	0.000
48	28.LowMC-L	0.000
49	19.PNSpine	0.000
50	18.ANSpine	0.000

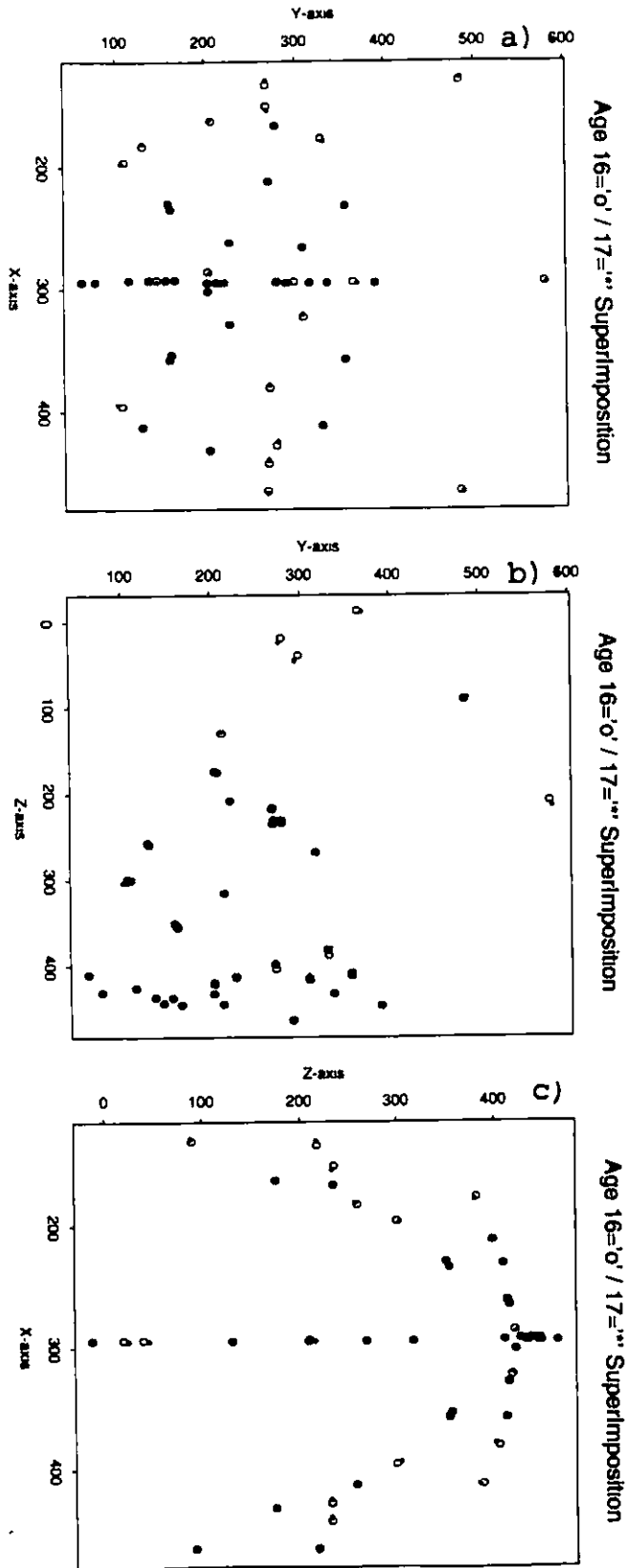


Figure 16. Procrustes Fit of landmarks from Age:16 to Age:17 in a) frontal view, b) lateral view, and c) axial view. Each landmark is ranked in a descendent order for shape modification.

Rank	Landmark	PDU
1	04.CondylL	6.325
2	39.AGoni-L	5.916
3	38.AGoni-R	5.745
4	34.LatCP-R	5.477
5	35.LatCP-L	5.385
6	03.CondylR	5.196
7	49.EuryonL	5.099
8	31.Menton	4.123
9	33.Gonio-L	4.000
10	15.Orbit-L	3.742
11	42.Inion	3.742
12	32.Gonio-R	3.742
13	17.Pirif-L	3.606
14	20.A Point	3.317
15	46.Mast-R	3.317
16	48.EuryonR	3.317
17	08.SupOrbR	3.317
18	41.Opistho	3.162
19	13.LtrOrbL	3.000
20	14.Orbit-R	3.000
21	43.Endinio	3.000
22	30.Pogonio	3.000
23	05.MecPorR	3.000
24	16.Pirif-R	3.000
25	37.CenRA-L	2.449
26	10.MedOrbR	2.449
27	36.CenRA-R	2.449
28	02.Basion	2.236
29	09.SupOrbL	2.236
30	18.ANSpine	2.236
31	06.MecPorL	2.236
32	23.UppMC-R	2.236
33	45.Rhinion	2.236
34	24.UppMC-L	2.236
35	47.Mast-L	2.236
36	25.LowerIE	2.236
37	28.LowMC-L	2.236
38	44.Glabele	2.000
39	19.PNSpine	1.732
40	29.B-Point	1.414
41	01.Sella	1.414
42	27.LowMC-R	1.414
43	21.Supdent	1.414
44	50.Vertex	1.414
45	11.MedOrbL	1.000
46	40.Opisthi	1.000
47	12.LtrOrbR	1.000
48	26.Infrade	1.000
49	22.UpperIE	1.000
50	07.Nasion	1.000

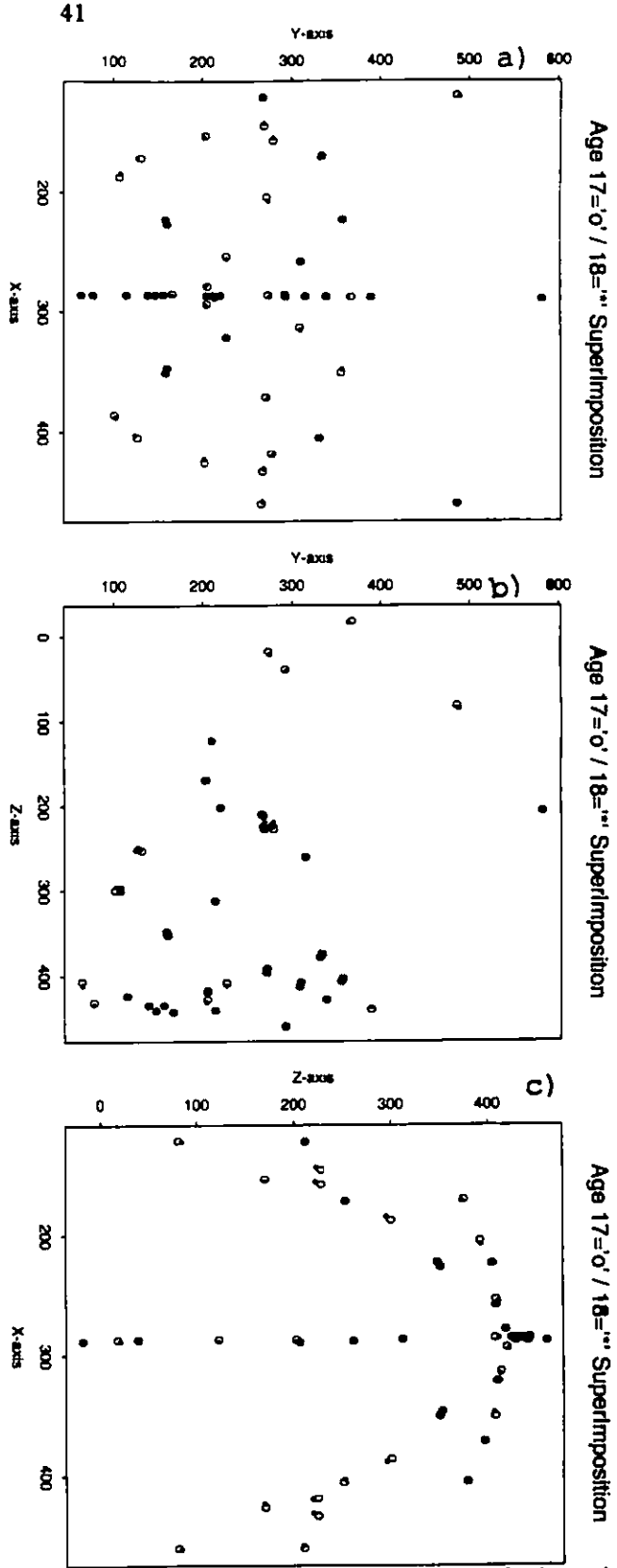


Figure 17. Procrustes Fit of landmarks from Age:17 to Age:18 in a) frontal view, b) lateral view, and c) axial view. Each landmark is ranked in a descendent order for shape modification.

DISCUSSION

There are two types of bias not controlled for in this study. First, the reproducibility of the landmark identification activities (i.e., intra-operator variance) was not tested. This could be tested by comparing the digitizing of several radiograph pairs on different occasions, widely separated in time. The second factor that can affect reproducibility of the results presented here is the baseline "human" ability to perceive the landmarks digitized (inter-operator variance). To quantify this, one must undertake a statistical study of multiple operators attempting to digitize the same radiographic pairs. Without testing for these two types of reproducibility, the results presented here are of unknown precision and thus cannot be assumed valid. Three other operators (A. Gasparetto, S. Park, and M. Valiathan) and I are currently involved in a larger validation study of these methods at the Bolton-Brush Growth Study Center.

The data for this study was analyzed on two different levels. The first approach was to use Procrustes Distance Units (PDU), to quantify the amount of shape change that occurred between each age group pair. The second approach was to determine the percentage of the overall change in shape regionally by normalizing the inter-age data. Five different craniofacial areas are discussed (anterior vault, posterior vault, maxilla, mandible, and mid-face). This analysis presents growth and remodeling effects in all directions.

Innumerable craniofacial growth and development studies have been presented in the past. However, it is significant to note that this appears to be the first three-dimensional longitudinal study of craniofacial growth and development. Thus, direct comparisons of this study's results with previous reports based on two-dimensional data may not be reasonable. Moreover, many studies combine male and female results. The discussion of this study compares the results to appropriate earlier findings.

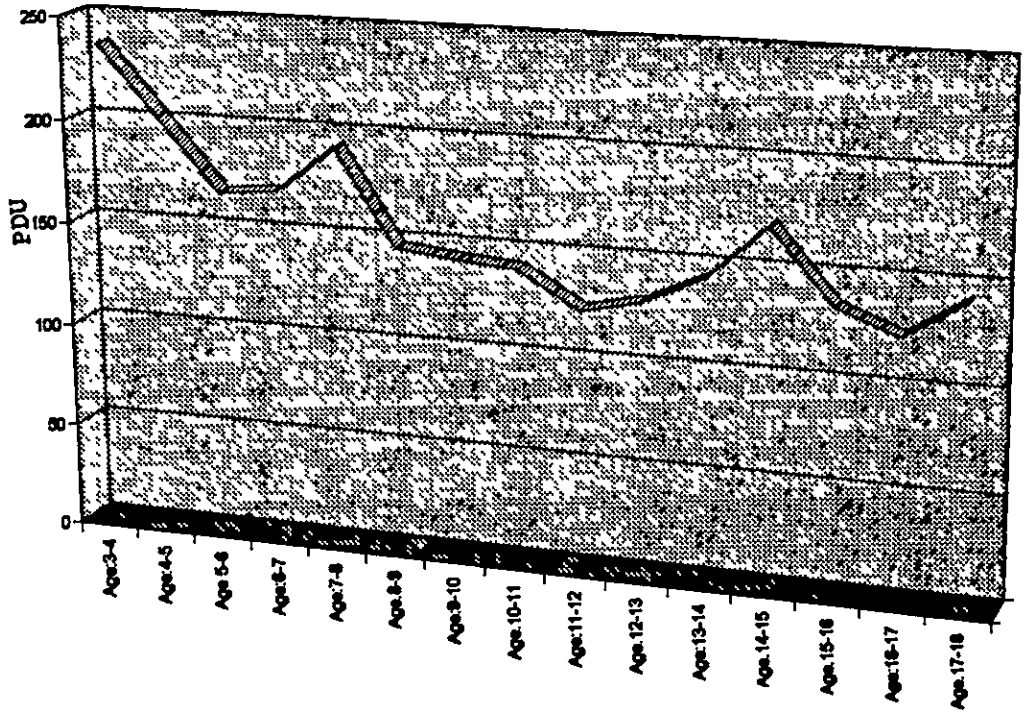


Figure 18. Overall Shape Change for Sixteen Female Bolton Faces from Age 3-18.

The sum Procrustes distance for all fifty landmarks is surveyed here. The level of shape change between all landmarks from year to year in this study is displayed in Figure 3. It represents the overall shape change of this landmark region within the human skull, mandible and teeth.

The 3-4 age period shows the highest amount of shape variation with 235.89 PDU (Procrustes Distance Units),

followed by ages 4-5, 202.26 PDU. On the other hand, ages 16-17 exhibit the least amount of morphological shift with a total of 124.62 PDU.

The landmark that shows the most variation within all periods is vertex (see Glossary for landmark definitions) with an overall relocation of 90.34 PDU. It shifts the most during the 3-4 age period, 14.04 PDU. The least relocation occurs during the 17-18 age group, with 1.414 PDU. However it is suspected that the high degree of plasticity of this landmark may be due to human difficulty in locating this point on plain film x-ray images. One problem is that vertex is cut off in many adolescent lateral films.

The landmark that shows the least shape variation is the Posterior Nasal Spine, 24.83 PDU overall, with the 11-12 and 16-17 age groups registering 0.0 PDU.

The overall shape modification shows its highest values at ages 3-4, thereafter stable shape change occurs around two moderate peaks, ages 7-8 and 14-15. This is in partial agreement with Moore et al. (1990) who report post-infant peaks at ages 7-8 and 11-12.

Female craniofacial growth after age 14 has been reported by Foley and Mamandras (1992). However, it

appears well established that the majority of shape modification occurs during the 3-9 age period (Singh, Savara 1966; Buschang et al. 1989; Nanda, Ghosh 1995).

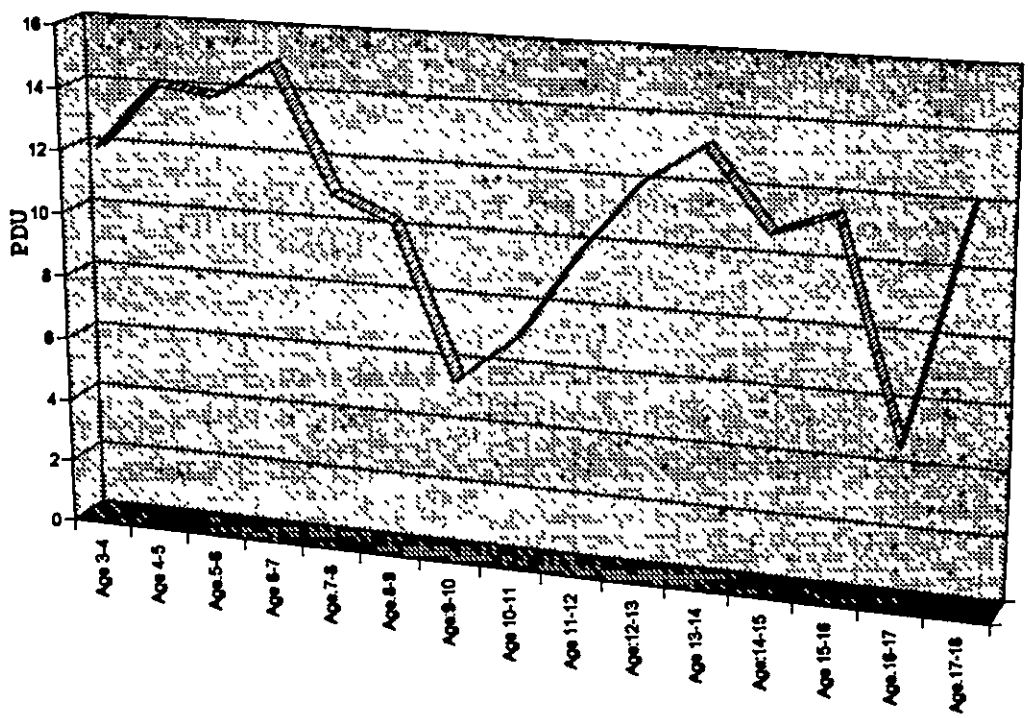


Figure 19. Unweighted Mid-Face Shape Change for Sixteen Female Bolton Faces from Age 3-18.

Mid-face shape change is evaluated through a group of five landmarks: Rhinion, piriform right and left, nasion, and anterior nasal spine.

The greatest variation of the mid-face region occurs during the 6-7 age group, 15.01 PDU, and the least, during the 16-17 age group, 4.83 PDU. Greatest positional modification in ages 6-7 agrees with observations by Snodell et al. (1993).

Of the five landmarks that form the mid face region, Left Piriform shows the greatest shift, 38.58 PDU, overall. It displays its greatest shape variation, 4.58, in the 6-7 age group, and the least, 1.41, within the 9-10, 10-11, and 16-17 age groups.

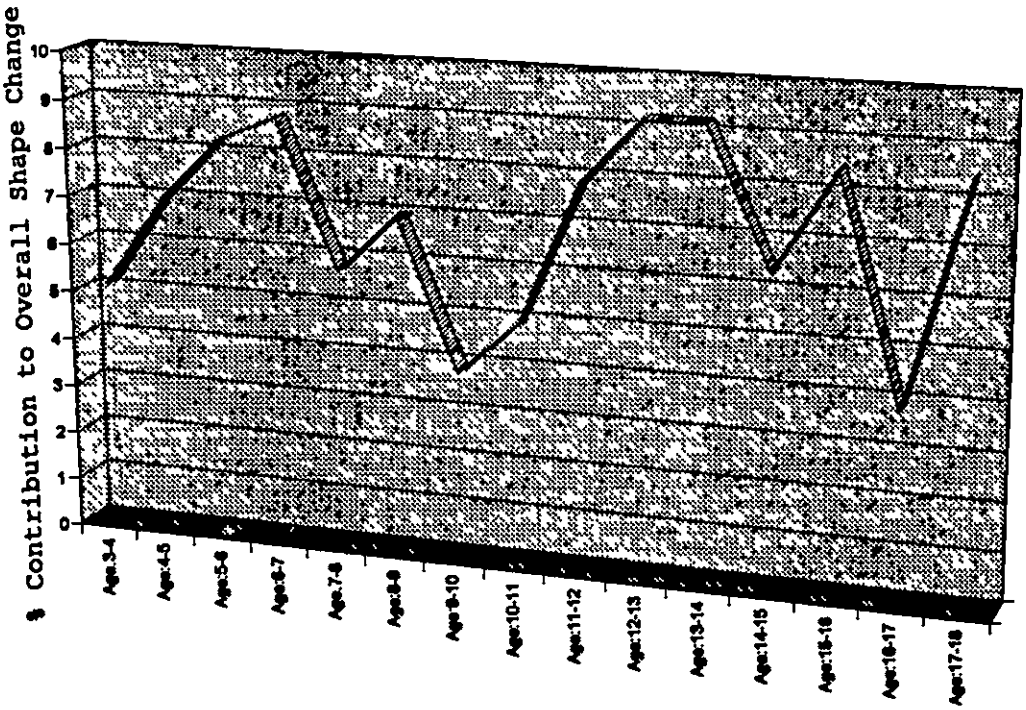


Figure 20. Relative Mid-Face Shape Change for Sixteen Female Bolton Faces from Age 3-18.

Amongst all the mid-face landmarks the Anterior Nasal Spine shows the least shape variation, 26.26 PDU. It moves most in the 12-13 age group, 3.16 PDU, and least, 0.0 PDU, in the 6-7, 9-10, and 16-17 age groups.

The direction of relocation of the mid-facial region, represented by these landmarks, varies. Rhinion and nasion in lateral view move in an anterosuperior direction, Piriform shows no superoinferior movement, and ANS shows an anteroinferior shift. The Piriform landmarks are the only mid-face landmarks analyzed which are not in the midline. They exhibit a slight lateral enlargement, a finding supported by Elmajian (1959) and Snodell et al.(1993).

The mid-face makes an average contribution of 6.9% to overall craniofacial shape modification. Its greatest proportion is in the 12-13 age group, 9.21% of overall change (an average of 1.8% per landmark), and its lowest level of participation is in the 9-10 age group, 3.87%.

Posterior Vault Shape Change

A total of nine landmarks form the Posterior Vault group: euryon (right and left), mastoidale (right and

left), opisthocranion, opisthion, inion, endinion and basion.

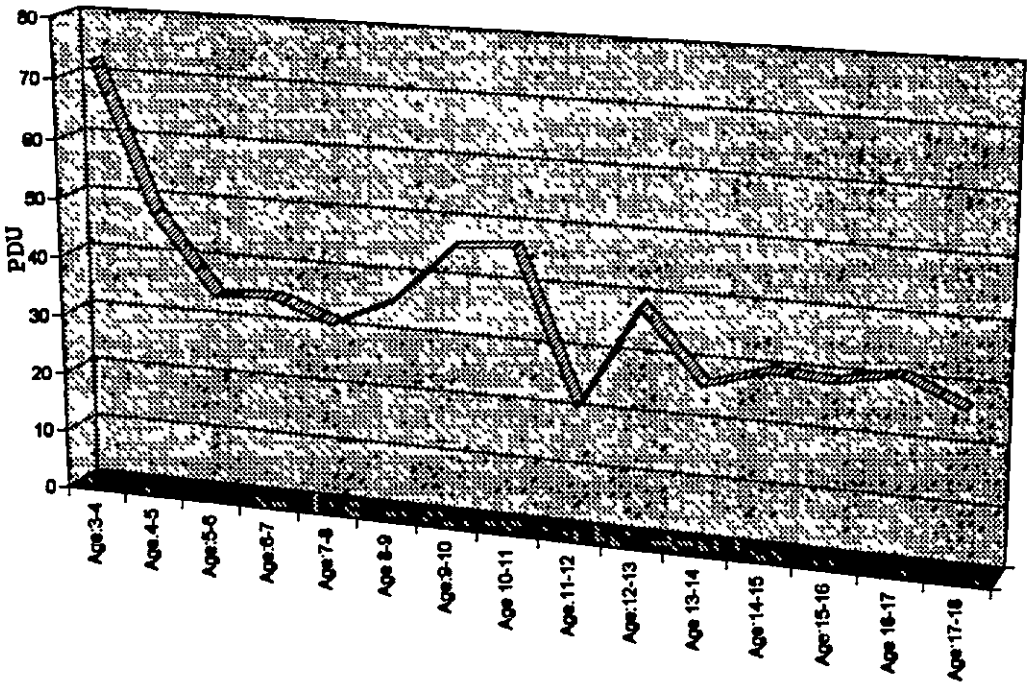


Figure 21. Unweighted Posterior Vault Shape Change for Sixteen Female Bolton Faces from Age 3-18.

The highest rate of shape modification is demonstrated by the 3-4 age group with 72.76 PDU. This concurs with Snodell et al. 's (1993) results. The lowest amount of relocation, on the other hand, occurs in the 11-12 age group, 21.57 PDU.

The landmark which contributes the highest amount of shape variation is opisthion, totaling 71.73 PDU, with an

average of 4.8 PDU per group. Basion's position varies the least, totaling 47.22 PDU, with an average of 3.15 PDU accumulation per group.

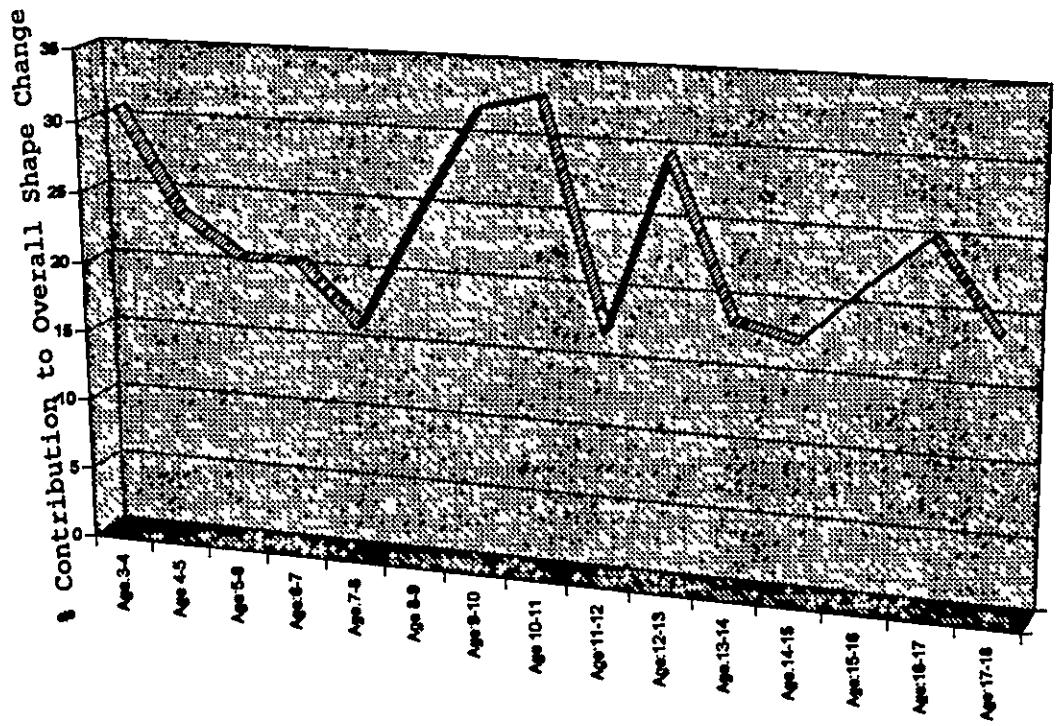


Figure 22. Relative Posterior Vault Shape Change for Sixteen Female Bolton Faces from Age 3-18.

The direction of shape change in this region is best divided into two periods. The earlier period shows all landmarks moving slightly posteriorly. In the later period these landmarks show an anterior movement. The cranial width (Bi-Euryon) shows a slight medial shift,

most likely due to remodeling. This adolescent pattern differs from that reported by Snodell et al. (1993), which suggests a relative expansion of Bi-Euryon.

The Posterior Vault region contributes 23.4% of the overall shape modification. The 10-11 age group exhibits 33% (an average of 3.6% per landmark) of overall shape change, the region's great contribution. The 7-8 age group contributes the least, 16.35%.

Mandibular Shape Change

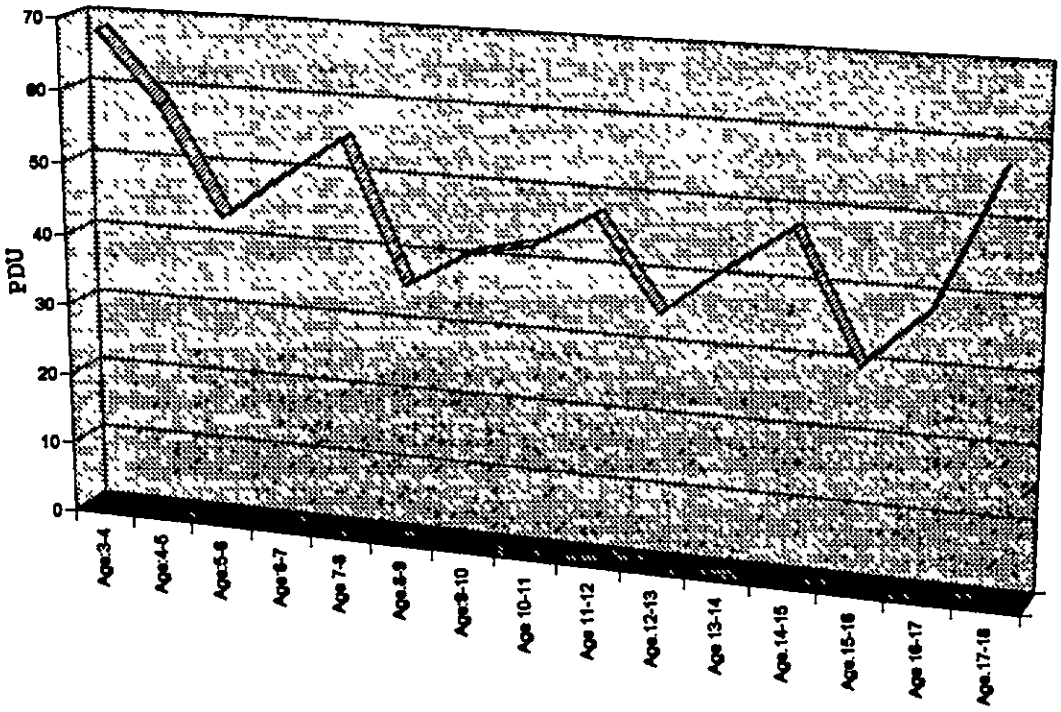


Figure 23. Unweighted Mandibular Shape Change for Sixteen Female Bolton Faces from Age 3-18.

The mandibular region consists of fifteen landmarks: Antegonial notch (right and left), lateral condylar pole (right and left), gonion (right and left), menton, pogonion, point B, lower first molar (right and left), infradentale, lower incisor edge, and condylion (right and left).

The largest shape change occurs in the 3-4 age group, 68.2 PDU. This is 1-2 years earlier than what Buschang et al. (1989) reports. The lowest change is in the 15-16 age group, with a shift of 30.3 PDU. The landmark that shows the greatest shape change is the Left Lateral Condylar Pole, which registers a 56.6 PDU total shape change, an average of 3.8 PDU per age group. Its peak is seen in the 10-11 age group, with 6 PDU, and its smallest change is in the 15-16 age group, 2.2 PDU.

The landmark that shows the least movement is Infradentale with a total change of 28.3 DPU, and an average of 1.9 DPU per group. Its greatest shift is in the 7-8 age group, 3.6 PDU. Its lowest shape change occurs in the 3-4, 8-9, 10-11, 15-16, and 17-18 age groups, all presenting 1.0 PDU shape change.

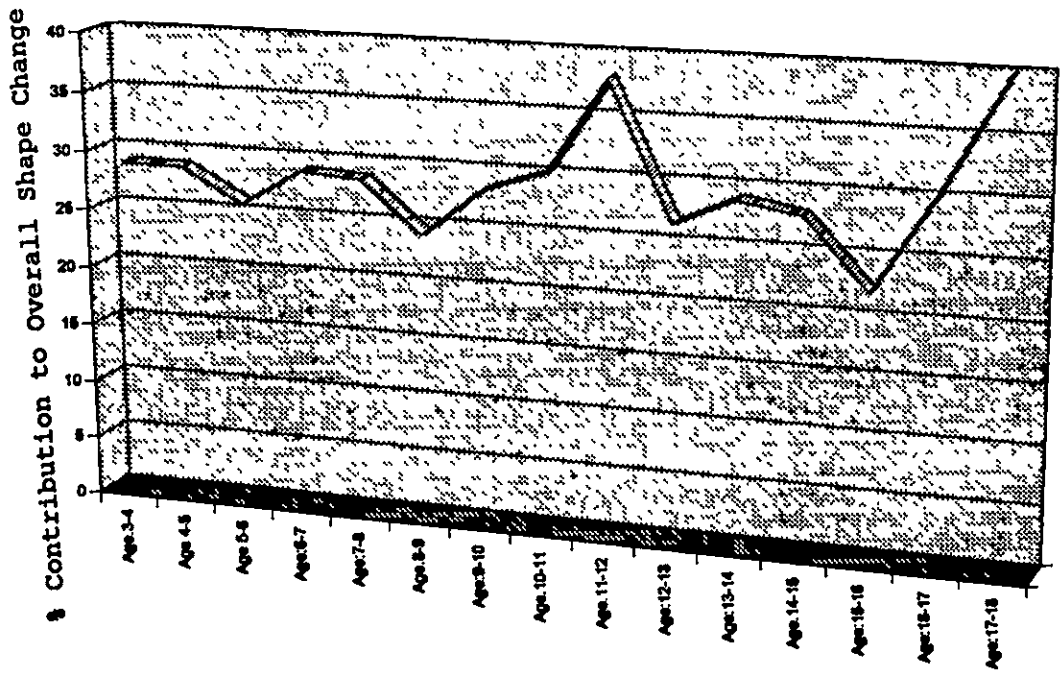


Figure 24. Relative Mandibular Shape Change for Sixteen Female Bolton Faces from Ages 3-18.

The mandibular region shows five peaks of shape modification: 3-4, 7-8, 11-12, 14-15, and 17-18 age groups. At least three of these periods of intense shape change appear directly related to permanent molar eruption (first, second, and third molars).

Shape modification of the mandibular region may be best described by separating the mandible into three areas: Condylar (condylion, lateral condylar pole), Corpus (gonion, antegonial notch), and anterior (menton, pogonion, point B, lower incisor, and infradentale). The

condylar area shows a superior and slightly posterior shift. This agrees with Bjork (1963) who reports a superior movement during condylar growth, with highly variable anteroposterior shifts. The corpus shows a posteroinferior shift, which concurs with Elmajian's (1959) findings. Finally, the anterior area of the mandible shows an anteroinferior shift. This result which differs from some authors (e.g., Buschang et al. 1992) who show superoposterior movement of landmarks B, infradentale, and lower incisor edge, and no anteroposterior movement of pogonion, but these findings are based on pooled male and female data. Our findings, agree with Elmajian, (1959) and Foley and Mamandras (1992), whose studies show anteroinferior movement of this region.

These results are in concordance with Foley and Mamandras (1992) description of growth in the 14-18 year period. They find that the mandible undergoes twice as much modification as the maxilla within that period. Bondevik (1995) reports that the mandible continues to illustrate incremental anteroposterior length and superoinferior additions through the early twenties.

The mandibular region contributes 29.3% of observed craniofacial shape modification. Its highest contribution is during the 17-18 age group. There it represents 40% of the total modification (an average of 2.7% per landmark). On the other hand, its lowest contribution, occurs in the 15-16 age group, where it presents 22.3% of the overall shape change.

Maxillary Shape Change

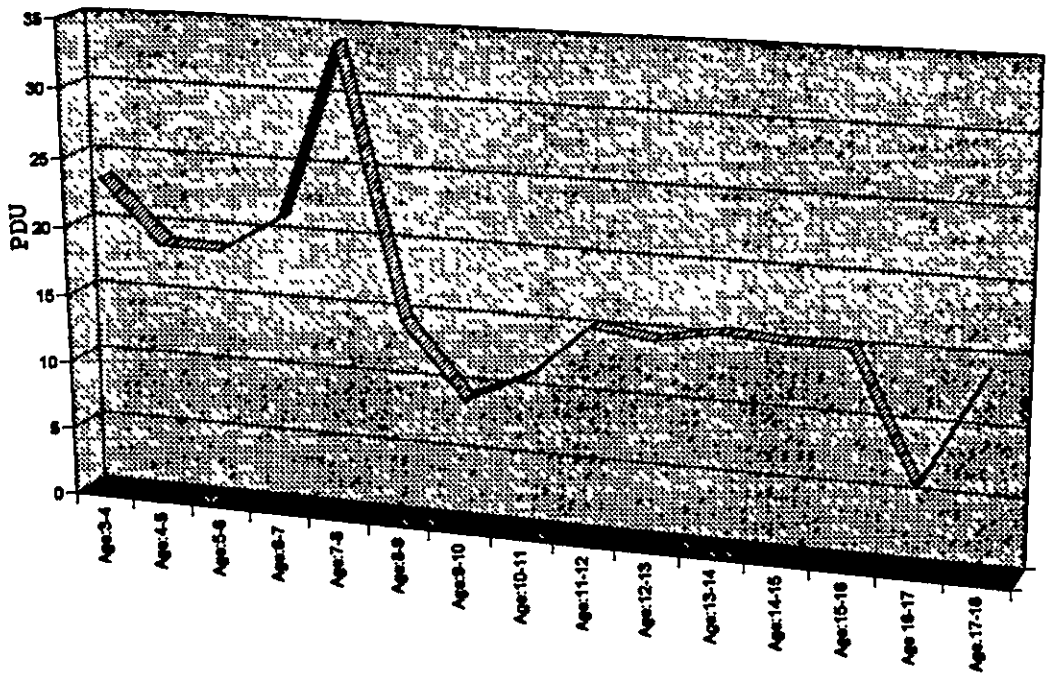


Figure 25. Unweighted Maxillary Shape Change for Sixteen Female Bolton Faces from Age 3-18.

The maxillary region consists of seven landmarks: PNS, point A, supradentale, upper incisor edge, upper first molars (right and left) and ANS.

The maxilllary region shows the greatest shape modification in the 7-8 age group, 34 PDU. The lowest amount of maxillary change occurs during the 16-17 age period, with 6 PDU. Our findings of the greatest shape modification periods are consistent with Enlow and Bang (1965), Singh and Savara (1966), Iseri and Solow (1990), and Nanda and Ghosh (1995). Actually, a graphic for maxillary shape modification based on Bjork's implant study (Iseri, Solow 1990) shows the same change peak ages as well as the relative stability after age nine.

The landmark that contributes the most to maxillary region shape change is the Upper First Molar with an overall change of 55.6 PDU. Its peak is at age 7-8 with 9 PDU, and its lowest mark is in the 10-11 and 16-17 age groups, both exhibiting 1.7 PDU.

The maxillary landmark that shows the least shape modification is PNS with an overall shift of 24.8 PDU. It registers a peak in the 15-16 age group with 4.5 PDU, and its nadir is in the 9-10 and 16-17 age groups, both with

0.0 PDU. This finding concurs with Broadbent (1937) and Baumrind et al. (1987).

Graphically, the female maxillary region displays anteroinferior growth, in the lateral view, with the posterior part of the maxilla horizontally steady. All the anteroposterior change is found in the anterior region. This finding is also supported by Broadbent (1937) and Baumrind et al. (1987).

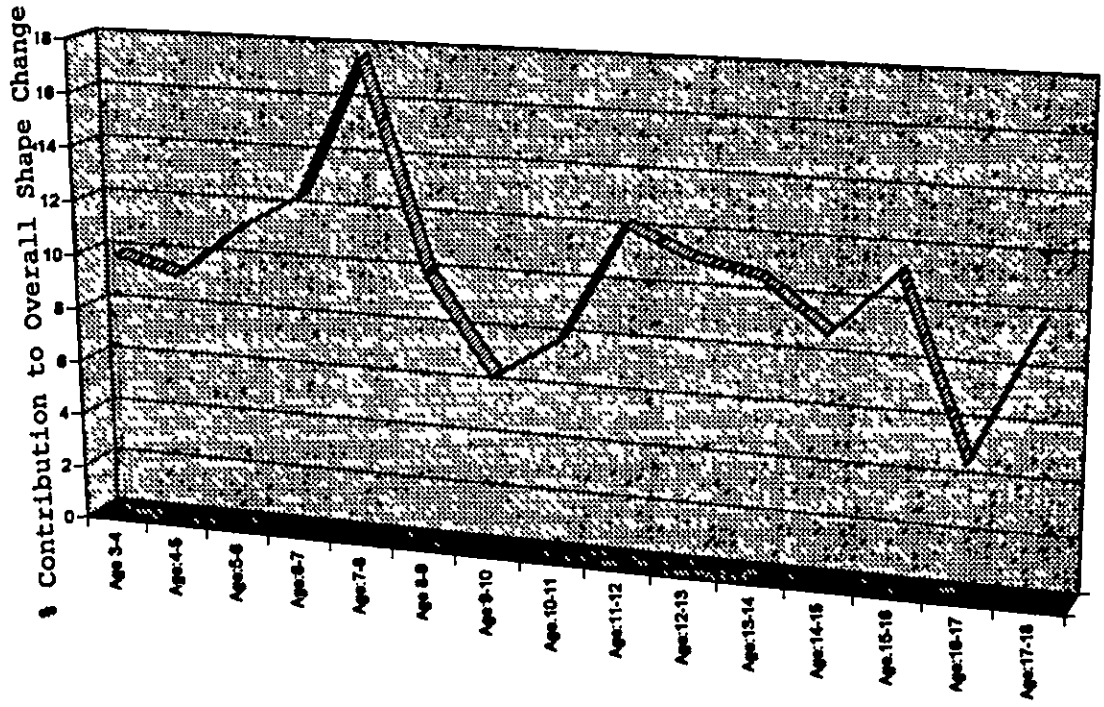


Figure 26. Relative Maxillary Shape Change for Sixteen Female Bolton Faces for Ages 3-18.

Although it appears to be no anterior movement of the molar dentition, it is important to note that in the

young child this landmark corresponds to a deciduous second molar; whereas by age eight it is the permanent first molar. Thus, the final anterior direction of the molar dentition is in concordance with Bjork and Skieller's (1983) reports.

In the frontal and axial view, the maxilla shows a posterolateral landmark movement. The result is overall enlargement and rounding of the palette.

The maxillary region contributes 10.3% of total craniofacial shape modification. Its highest contribution occurs in the 7-8 age group, 17.6% of the total (an average of 2.5% per landmark), and its lowest contribution is in the 16-17 age group, 4.8%.

Anterior Vault Shape Change

The last craniofacial landmark group analyzed was the anterior vault region, which was formed by twelve landmarks: Sella, nasion, superior orbitale (right and left), medial orbitale (right and left), lateral orbitale (right and left), orbitale (right and left), glabella and vertex.

The anterior vault region shows peak shape modification in the 4-5 age group, 58.8 PDU, and the least amount of change in the 11-12 age group, 24.3 PDU.

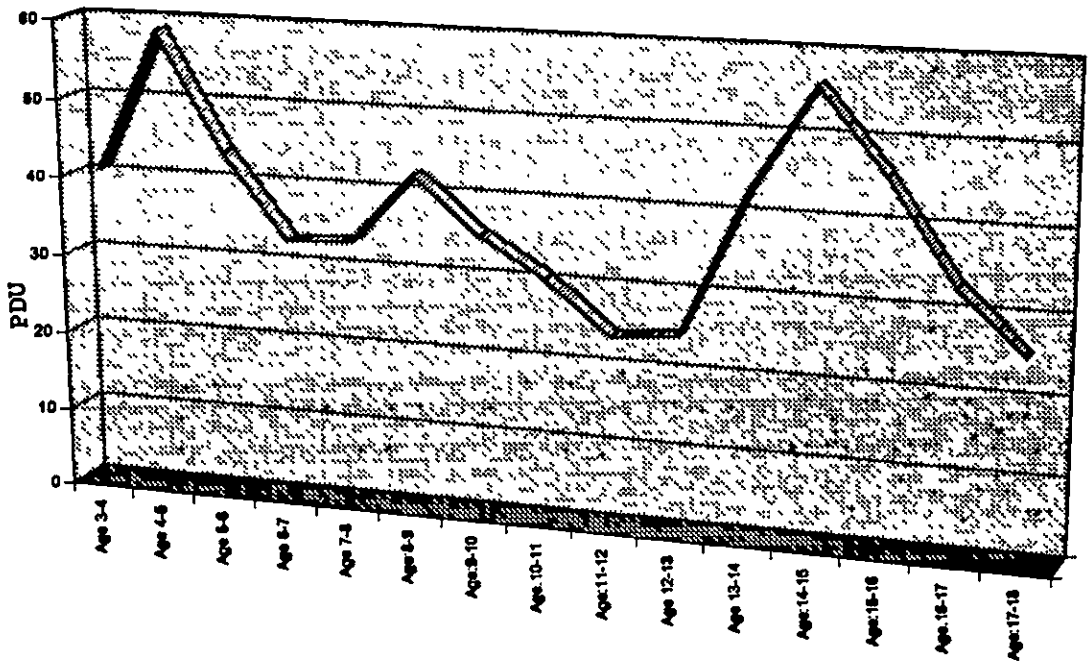


Figure 27. Unweighted Anterior Vault Shape Change for Sixteen Female Bolton Faces from Age 3-18.

As noted earlier, vertex shows 90.3 PDU. Its peak is seen in the 3-4 age group, 14 PDU, and its lowest shape variation occurs in the 17-18 age group, 1.4 PDU. Nasion, with an overall shift of 29 PDU, registers the least amount of change. It achieves a peak in the 3-4 age group with 5.0 PDU, and its lowest value in the 5-6, 9-10, 10-11, 16-17 and 17-18 age groups where 1.0 PDU is observed. These findings agree with Abraham (1969).

The direction of Anterior Vault landmark shape modification is not homogeneous. The circum-orbital landmarks, as well as nasion and sella, show very

similar, significantly superior movements. The upper circum-orbital landmarks show a slight posterior shift. This partially agrees with Moss (1955), who, using both male and female data, reports a superoposterior direction of orbital shift.

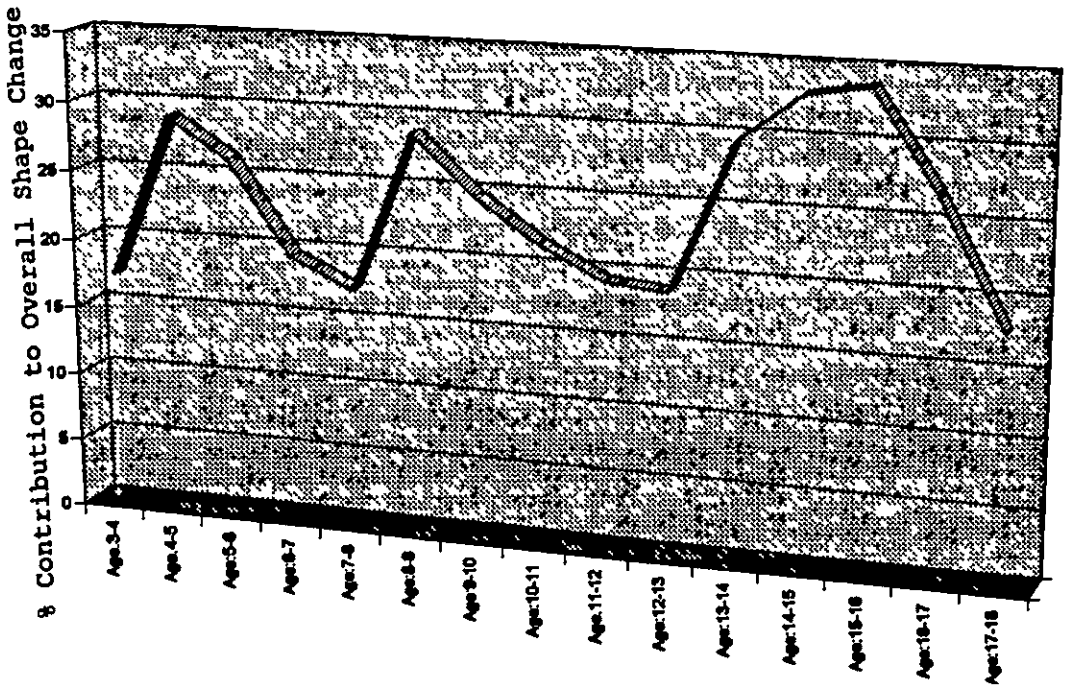


Figure 28. Relative Anterior Vault Shape Change for Sixteen Female Bolton Faces from Age 3-18.

In our results, sella and nasion both shift superiorly but also spread apart when seen in the lateral view. These landmarks present no significant lateral movements when seen in the frontal or axial views. In the

literature there are different opinions on the relational change that happens between nasion and sella. These opinions depend on what baseline is used for superimposition. Using different baselines, Ford (1958) found superior and Elmajian (1959) found inferior movement of both these landmarks. Both authors relate an anteroposterior spreading apart between these landmarks. Vertex and glabella move slightly towards the center of the head in all views. Glabella also shows a slight inferior shift.

The anterior vault region contributes 24.3% of overall craniofacial shape modification. Its peak contribution occurs in the 15-16 age group, 33.8% of the total. Its lowest contribution occurs in the 3-4 age group, 17.3%.

CONCLUSION

From its creation in 1925, the Broadbent-Bolton cephalometer has presented the possibility of three-dimensional (3D) data collection via biorthogonal cephalograms (plain film x-rays). However, work with 3-D data was not practical until the advent of computer graphics workstations and digital image handling software. This study used this technology to capture 3-D landmarks from sixteen female Bolton Face radiographic image series. These Bolton Study image series document longitudinal growth of the study participants during annual visits to the Bolton-Brush Growth Study Center between 1927 and 1959.

The collection of three dimensional landmark coordinates (x, y, z) from the female Bolton Face images required the following steps: a) growth series of sixteen lateral and frontal cephalometric x-ray individuals chosen from the Bolton Face sample were scanned, b) the 3dCEPH program was used to enhance image quality (specially contrast), c) the same software also assisted

the 3-D landmark identification and co-registration of landmarks seen in both frontal and lateral cephalograms via a software implementation of the Broadbent-Bolton Orientator, and d) use the 3dCEPH program to produce average landmarks from data sets collected for same-sex age groups (ages 3-18).

A longitudinal measure of shape change was produced via the Procrustes algorithm. This algorithm, via a least square fit, superimposes adjacent age group landmarks on a shared "centroid". Individual landmark and overall Procrustes shape distances in Procrustes Distance Units (PDU) were calculated. To better analyze the observed change, the craniofacial complex was separated in five regions: Anterior vault, posterior vault, maxilla, mandible and mid-face.

Overall it can be seen that the craniofacial complex undergoes continuous shape change during ages 3-18. Clinically this may be important as what is perceived as relapse may actually be lack of expected modification.

The posterior vault region demonstrates the greatest amount of shape change. Some of the shape variation seen may be due to the difficulty of identifying some of these landmarks. For example, vertex cannot be accurately

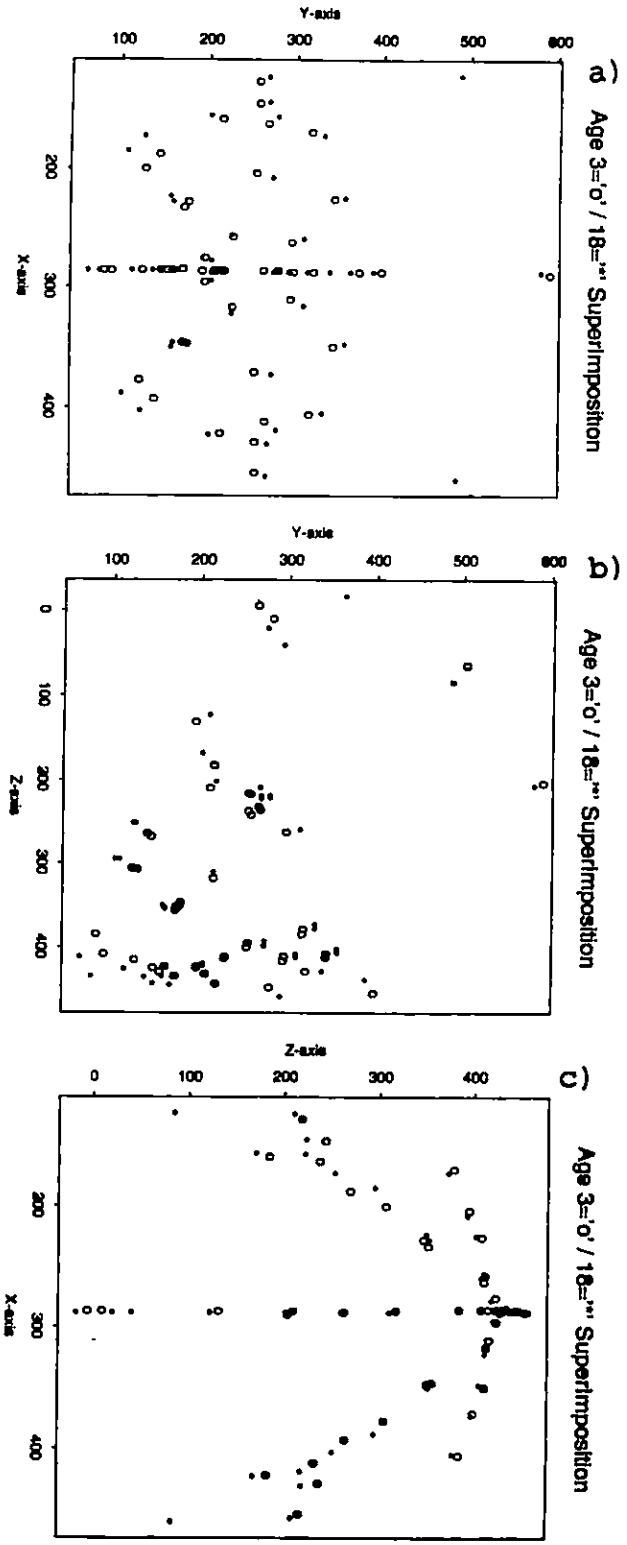


Figure 29. Procrustes Fit of Landmarks for Sixteen Female Bolton Faces for Ages 3-18 in a) frontal view, b) lateral view, and c) axial view.

detected in the lateral view of adolescent Bolton Faces.

The top of the head is cut off by the 8" x 10" film used. The same problem happens, tough less often, when opisthocranion is also cut off posteriorly in some lateral radiographs. The position of these landmarks is determined from the frontal image and on approximate siting to the lateral view using the Broadbent-Bolton Orientator horizontal lines and the available image information. Our results for the anterior and posterior vault indicate relocation towards the center of the head.

Traditionally the line passing through sella and nasion was assumed to be morphologically stable. Thus, early methods of superimposition of lateral tracings used this baseline. Our results indicate an upward and slight anteroposterior separation between these points in females. The pattern in males may be different. Bookstein (Bookstein 1991) discusses reference-frame invariant means, such as "shape coordinates", to use any pair of landmarks as baseline to obtain the same measure of shape variation of the remaining landmarks. These, and the method used here, also control for size differences simultaneously reporting geometric findings.

The female orbit seem to shift superoposteriorly

overall. Greater movement at orbitale has the juvenile rounded orbit appear more mediolaterally oblong.

When comparing the results obtained for the orbit (superoposterior change) with those from the mid-face (superoanterior direction), it can be concluded that these females become more leptoprosopic. This protrusive tendency is shared by the dentition, which also shows an anterior movement.

The major areas of interest to the orthodontist are the maxilla and mandible. According to this study, intervention in the female maxillary region which depends on a high rate of growth would have best results before age nine. For the mandible, five shape modification peaks are observed: 3-4, 7-8, 11-12, 14-15, and 17-18. These results might suggest to the practitioner when to focus mandibular treatment of females for anteroposterior skeletal change. Traditionally the entire period of adolescence has been deemed productive. Perhaps treatment limited to periods between 12-14 and 15-17 would be more productive with limited extension into adjacent ages.

APPENDIX 1

The total number of visits was 186 with an average of 11.5 visits per participant.

TABLE 2.--Visits of each of the Sixteen Female Bolton Faces for each Age Group

	Age at Visit																
Bolton Face No.	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Total
0115			X	X		X	X	X	X	X	X	X	X	X	X	X	13
0131		X		X	X	X	X	X	X	X	X	X	X		X	X	13
0133	X		X	X	X	X		X	X		X	X		X			10
1123							X	X	X	X	X	X	X	X	X	X	10
1197	X			X	X	X	X	X	X		X	X	X			X	11
1208		X	X	X	X	X	X	X	X	X	X	X	X	X	X		14
1212				X	X	X	X	X	X	X	X	X	X	X	X	X	13
1242	X			X	X	X	X	X	X		X	X		X	X		11
2030	X	X	X	X	X	X		X	X		X	X		X			11
2097				X	X	X	X	X	X	X	X		X	X	X	X	12
2140				X	X		X			X	X	X	X	X	X		09
2144		X	X		X	X	X	X	X		X	X		X	X	X	12
2157	X	X	X	X	X	X	X	X	X		X	X					11
2187			X	X	X	X	X	X	X	X	X		X	X	X		12
2462	X	X		X	X	X	X	X		X	X	X		X	X		12
3037	X	X	X	X	X	X	X	X	X			X					10
2558	X	X	X	X	X	X	X	X	X	X	X		X	X			13

GLOSSARY

The landmarks and correspondent definitions used in this study are here presented in alphabetical order:

1. **A Point:** Most posterior point in the lateral view along the line between the anterior nasal spine and the alveolar crest of the upper central incisor.

2. **Antegonial Notch (bilateral):** The point of maximum curvature that is the greatest depth of incurvation. The notch is found between the posterior third and anterior two thirds of the inferior mandibular border (i.e., between the ramus and corpus). It is not necessarily the highest point in Frankfort horizon.

3. **Anterior Nasal Spine:** Sharp process, which is a prolongation of the superior-anteriormost parts of medial junction between both maxillae. It is most apparent in the lateral view and is obvious when sighing across to the midline of the frontal view.

4. **B Point:** Most posterior point in the lateral view along the line between the alveolar crest of the lower central incisor and pogonion.

5. **Basion:** Point where the median sagittal plane of the skull intersects the lowest point on the anterior margin of the foramen magnum.

6. **Central Incisor Root Apex (bilateral):** Recognized in the lateral view. It is the intersection of the superior poles of the roots of the upper central incisor roots. Not apparent in children under 6 years of age. The top of the deciduous incisor root is used in

children 2-6 years old. Broadbent Orientator alignment to midline for frontal view.

7. **Condylion (bilateral):** The most superior point on the superior curvature of the condyle. This point is usually difficult to view in the lateral view. There is often the need to estimate the right and left landmarks based on nearby structures. It may be easier to begin with the frontal view and sighted across the orientator to the lateral view. Assuming the head position is correct and there is no significant right-left asymmetry, the right condylion is located more anteriorly than left condylion.

8. **Endinion:** Most anteriorly projecting point at the confluence of sinuses. The point is easily located at the inferior terminus of the superior saggital sinus and the posterior terminus of the tentorium and beginning of the transverse sinus.

9. **Euryon (bilateral):** The most prominent lateral point on each side of the skull in the area of the parietal and occipital bones.

10. **Glabella:** The most anterior point on the midline of the brow.

11. **Gonion (bilateral):** The external angle of the mandible, located on the lateral radiograph by bisecting the angle formed by tangent of the posterior border of the ramus and the inferior border of the mandibular corpus (i.e., a line passing under the inferior border below menton to the posterior to gonion). This can be located with a protractor, although future versions of 3dCEPH will have an on-screen tool to find this point. Note: when this point is sighted across it to the frontal image it will usually not correspond to the widest point in the gonial region. However, the intersection with the sighting line should be taken as gonion in the frontal view. Assuming the head

position is correct and that there is no significant asymmetry, the right gonion point is located more anteriorly and inferiorly. The vertical height of this point can be checked on the frontal cephalogram, although note that it is not the widest point in most cases.

12. **Infradentale:** The superiormost point of the alveolar bone between both central upper incisors.

13. **Inion:** External occipital protuberance. Superiormost attachment point for nuchal ligament. Defines border between scalp and neck muscles. Can be elongate in adult males.

14. **Lateral Condylar Pole (bilateral):** This point is seeing in the frontal view as most lateral tip of the condylar head. In the lateral view trace the anterior and posterior condylar borders superiorly. Sight across the Broadbent Orientator to an intersection with the posterior border of the mandible. The landmark is at the midpoint of the line connecting this point to a horizontal intersecting the anterior condylar borderline (aka MGH point).

15. **Lateral Orbit Point (bilateral):** The superolateral-most point on the orbital outline, roughly corresponding to the frontozygomatic suture. Assuming the head position is correct and that there is no significant asymmetry, the right lateral orbit point is located more superiorly and anteriorly.

16. **Lower First Molar Cusp (bilateral):** The distobuccal cusp tip of the lower first molar. Often superimposing the Bolton Standards templates on the molar teeth helps in recognition of this point. Assuming the head position is correct and there is no significant asymmetry in the dentition, the right first

molar cusp is located more anteriorly and inferiorly than the left first molar cusp.

17. **Lower Incisor Edge:** Recognized in the lateral view. The intersection of the superior tips of the central lower incisor crowns. Broadbent Orientator alignment to midline for frontal view.

18. **Mastoidale (bilateral):** The lowest point on the contour of the mastoid process.

19. **Mechanical Porion (bilateral):** Founded by using Broadbent template. After placing the ear rod template in position on the lateral films, the center of the ring forms an axis of rotation if any rotation is necessary to get alignment of the frontal and lateral views. Mechanical porion is at the top of this ring produced primarily by the smaller ear rod ring, which is the closest to the film. The right and left mechanical porion are located in the frontal view by tracing the centerline of the ear rod to its intersection with the bony external auditory meatus (on the temporal bone, not the skin).

20. **Medial Orbit Point (bilateral):** Located in the frontal view first and sighted across to the lateral image. The top of the lacrimal crest (lacrimale), anterior to nasolacrimal duct. There is often a small crest posterior to this duct. In most cases the paranasal sinuses and ethmoid sinuses will produce two small spaces medial to the lucency within the nasolacrimal duct. When viewed on a dry skull, this point is the medial termination of the inferior orbital crest on the lacrimal bone or the frontal process of the maxilla in cases where the lacrimal bone does not surround the duct. Assuming the head position is correct and that there is no significant asymmetry, the right medial orbital point is located more superiorly and anteriorly.

21. **Menton:** The most inferior point on the symphysis of the mandible in the median plane. Seen in the lateral radiograph as the most inferior point on the symphysial outline when the head is oriented to Frankfort horizon.

22. **Nasion:** On the lateral film find most posterior point on the arc between glabella and rhinion, roughly approximating the nasofrontal suture. Use the Broadbent Orientator to find this point's intersection with the midline.

23. **Opisthion:** Point where the median sagittal plane of the skull intersects the lowest point on the posterior margin of the foramen magnum.

24. **Opisthocranion:** Most posterior point on the external surface of the occipital bone. Usually between obelion (can be cut off) and inion. Usually slightly above lambda (not discernable on plain film x-ray).

25. **Orbitale (bilateral):** The most inferior point on the inferior orbital rim in the lateral view. It is used in conjunction with the porion to determine the Frankfort horizontal. Assuming the head position is correct and that there is no significant asymmetry, the right orbitale point is located more anteriorly.

26. **Piriform (bilateral):** In the frontal view it is the widest point in the aperture. Note that the borders of the nasal cavity are much more radiopaque than the piriform aperture line, which is often faint. It is, roughly, the posterior point on the lateral view of the nasal aperture line; however, the Broadbent Orientator can help in selecting this point.

27. **Pogonion:** The most anterior point on the symphysis of the mandible seen in the lateral view when the head is oriented to Frankfort horizon.

28. **Posterior Nasal Spine:** Process formed at the posteromedial ends of the posterior borders of the two palatine bones (hard palate). This point corresponds to a point at the intersection of a tangent line representing the pterygomaxillary fissure and the horizontal plane of the hard palate.

29. **Rhinion:** The tip of the bony nose. It is the anteriormost external point on the internasal suture.

30. **Sella:** Hypophyseal, or pituitary, fossa or sphenoid bone lodging the pituitary body. The observer makes a best guess of the center point of the pituitary fossa, as seen in the lateral radiograph and located by inspection.

31. **Supradentale:** The inferiormost point of the alveolar bone between both upper central incisors.

32. **Supraorbital Point (bilateral):** The most superior point of the supraorbital line. Roughly corresponds to the lateral border of the supraorbital notch. Assuming the head position is correct and there is no significant asymmetry, the right supraorbital point is located more superiorly and anteriorly. The frontal image can be used to confirm the height of this point.

33. **Upper First Molar Cusp (bilateral):** The distobuccal cusp tip of the upper first molar. Often superimposing the Bolton Standards templates on the molar teeth here helps in recognition of this point. Note that this is a departure from the traditional cephalometric use of the mesiobuccal cusp of the first molar. The mesiobuccal cusp's location is more difficult to estimate in three dimensional plain film x-ray cephalometrics. Assuming the head position is correct and there is no

significant asymmetry in the dentition, the right first molar cusp is located more anteriorly and inferiorly than the left first molar cusp.

34. **Upper Incisor Edge:** Recognized in the lateral view. The intersection of the inferior tips of the upper central incisors crowns. Broadbent Orientator alignment to midline for frontal view.

35. **Vertex:** The highest point of the head when the head is orientated in the Frankfort Horizontal plane. The bony landmark in the middle of the top of the skull, where the coronal and sagittal sutures cross.

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