Growth of Cranial Base and Vault Dimensions in Children

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Abstract Lengths and angles within the cranial base and vault were measured in cephalometric radiographs of 220 boys and 177 girls ranging in age from 0 to 18 years. These children were participants in The Fels Longitudinal Growth Study. The present study is based on mixed longitudinal data derived from 1861 radiographs for boys and 1401 radiographs for girls. In this study, the anatomical parts of the cranial base are designated as follows: cranial base (nasion-basion), anterior cranial base (nasion-sella), fronto-ethmoidal segment (nasion-sphenoidale), presphenoid segment (sphenoidale-sella), posterior cranial base (sella-basion), basisphenoid segment (sella-sphenoccipital), and basioccipital segment (sphenoccipital-basion). Endocranial points are used in the calvarial area for the vertex and anterior and posterior limits. Moreover, three angles are measured (nasion-sella-point A; nasion-sella-posterior nasal spine). Changes with age in the mean values for each dimension are described. The statistical significance of the observed age changes was tested by linear regression analysis for each variable after dividing the samples into three age groups (0-3, 4-6, 7-18 years). Contrary to reported findings, both basisphenoid and basioccipital segments increase steadily with age in each sex. The angle sella-nasion-point A decreases until the age of 10 years in boys and 9 years in girls; at older ages there is a tendency to increase with age in each sex.

Craniology has been a focus of interest throughout the history of physical anthropology; consequently much cranial data have been collected. Growth in the cranial base has been, also, a matter of concern for orthodontists in relation to that of the facial region; some angles in the cranio-facial region have been used in orthodontic diagnosis, case assessment, and treatment planning.

The morphology of the cranium is the result not only of bone growth but of the integral growth of all its components, namely, brain, meninges or viscera (INMAN, 1934). The growth data of a particular bone may, therefore, be meaningful when they are considered in the functional matrix of the cranium (MOSS et al., 1956; MOSS and YOUNG, 1961), and are correlated at least with those of other bony struc-
tures in the cranial region (OHTSUKI, 1977a, 1978). In this context, concomitant growth data for two or three dimensions in each cranial bone will be more informative than data for one dimension (OHTSUKI, 1977b, 1980).

The aim of the present study is to describe the serial age changes of cranial base and vault dimensions which are all in the midsagittal plane; attention is paid to the interrelationships among these dimensions. The cranial base is divided into its segments for this purpose, i.e., frontoethmoidal, presphenoid, basisphenoid, and basioccipital; these divisions will be helpful for a discussion in relation to growth sites (FORD, 1958). Three basal angles are also employed as a reference for any relocation of cranial landmarks over the ages 0-18 years.

MATERIALS AND METHODS

The present study was based on serial cephalometric radiographs of 220 boys and 177 girls taken annually from 0 to 18 years within one month of each birthday. These white individuals live in Southwestern Ohio and are participants in The Fels Longitudinal Growth Study. This investigation is based on mixed longitudinal data derived from 1861 radiographs for the boys and 1401 radiographs for

Fig. 1. Schematic drawing of landmarks used in the present study. SE' is geometrically projected on the S-N line from SE keeping the distance from S constant. SO' is also projected on S-BA line from SO keeping the distance from S constant.
the girls. Each radiograph was traced by a single individual and all the cranio-
metric points were verified by another.
The following craniometric points were used (Fig. 1):
N—nasion, the anterior end of the naso-
frontal suture;
S—sella, the center of the hypophyseal
fossa;
BA—basion, the most postero-inferior
point of the clivus;
SE—sphen-o-ethmoidal point, i. e., the
point were the margin of the greater
wing of the sphenoid crosses the crib-
riform plate or planum sphenoidale.
When there is inexact superimposition
of the two wings of the sphenoid, the
point is midway between the shadows
of the two wings;
SO—the midpoint of the endocranial
end of the spheno-occipital synchondro-
nosis;
Point A—subspinale, the deepest midline
point on the premaxilla between the
anterior nasal spine and prosthion
(DOWNS, 1948);
VX—vertex, the furthermost point from
sella on the endocranial margin of
the vault;
A—anterior, and P—posterior endocra-
nial points selected to obtain the
maximum endocranial diameter and
PNS—posterior nasal spine, i.e., the tip
of the posterior spine of the palatine
bone.
SE is projected geometrically onto the
S–N line as SE', keeping the distance from
S constant. SO is also projected onto
the S–BA line as SO' keeping the distance
from S constant.
These points were used to measure the
following distances: N–S, N–SE', SE'–S,
All distances were measured with Helios
calipers to the nearest 0.1 mm and cor-
corrected for radiographic enlargement. Three
angles were measured (N–S–BA, S–N–A,
N–S–PNS); each to the nearest 0.5 degree.
In the text, the anatomical parts of the
 cranial base are designated as follows:
 anterior cranial base, N–S; fronto-ethmoi-
dal segment, N–SE'; presphenoid segment,
SE'–S; posterior cranial base, S–BA;
basisphenoid segment, S–SO'; and basioc-
cipital segment, SO'–BA. In addition, the
distance BA–N was taken as a general
measure of the cranial base length.
Endocranial points were used in the
calvarial area (S–VX and A–P) because
they are, presumably, more closely related
to brain size than are ectocranial points,
The statistical significance of the ob-
served age changes was tested by linear
regression analysis for each variable after
dividing the samples into three age groups
(0–3, 4–6, 7–18 years); some changes in
growth trend occur about the ages of 3
and 6 years when cessations of growth
activity at sutural areas or synchondroses
are reported (SCOTT, 1958; COBEN, 1961;
OHTSUKI, et al., 1981). The regression anal-
ysis involved testing the significance of the
tendency for the slope to differ from
zero (no change with age).

RESULTS
Basic descriptive statistics for the sam-
ple by age and sex are given in Tables 1.
Fig. 2. Means for BA-N, N-S and S-BA (mm) for boys and girls. Boys are represented by closed circles, and girls by open circles. Semi-closed circles mean that plots for both sexes are superimposed due to the scale of y-axis.

Fig. 3. Means for N-SE' and SE'-S (mm) for boys and girls. Boys are represented by closed circles, and girls by open circles.

and 2 and the means are shown graphically in Figures 2-6.

The N-S length increases rapidly to 2 years and then slowly until 18 years (Tables 1 and 2; Fig. 2). Considering the components of this dimension, i.e., N-SE' and SE'-S, it is observed that N-SE' increases steadily during the period studied for each sex. Some acceleration is, however, perceptible at pubescence. SE'-S increases in a decelerating manner from 2 to 6 years after which little
Table 1. Means and standard deviations for 9 cranial base and vault dimensions with 3 angles in boys (0-18 years).

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Cranial Base and Vault Dimensions
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F. OHTSUKI, D. MUKHERJEE, A. B. LEWIS and A. F. ROCHE
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Table 2. Means and standard deviations for 9 cranial base and vault dimensions with 3 angles in girls (0–18 years).
Table 2. (Cont’d) Means and standard deviations for 9 cranial base and vault dimensions with 3 angles in girls (0–18 years).

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increase in size is noted in either sex (Tables 1 and 2; Fig. 3). By regression analysis, the increases in the values for these three dimensions are statistically significant for each sex at the 0.01 level in each of the three age groups (0-3, 4-6, and 7-18 years).

The S-BA length increases constantly but slowly after the age of 2 years (Tables 1 and 2; Fig. 2). Dividing this dimension into its segments, i.e., SO'-BA and S-SO', SO'-BA increases steadily; S-SO' shows the same trend, even though the absolute values are smaller than those for SO'-BA. By regression analysis, increases in the values for these three dimensions are significant for each sex at the 0.01 level in each of the three age groups (0-3, 4-6, and 7-18 years; Tables 1 and 2; Fig. 4).

In one sense, BA-N includes all the above dimensions. BA-N tends to increase constantly from 2 to 10 years, following the rapid growth activities of the neonatal period. Later there is a slight acceleration in each sex (Tables 1 and 2; Fig. 2). The increases of values with advancing age are statistically significant (0.01 level) for each sex throughout the three age groups.

The S-VX length increases to be almost adult size at 7 years (Tables 1 and 2; Fig. 5). By regression analysis, the tendency of the values to increase is significant at the 0.01 level in each sex for the first age group (0-3 years). In the second age group (4-6 years), the level of significance is 0.05 for boys but 0.01 for girls. In the third age group (7-18 years), a tendency to increase is not statistically significant in either sex. The A-P length also reaches approximate adult size at 7 years of age; the increments after this age are very small (Tables 1 and 2; Fig. 5). An increase with age, however, is statistically significant at the 0.01 level in each sex except in the third age group.

Fig. 4. Means for SO'-BA and S-SO' (mm) for boys and girls. Boys are represented by closed circles, and girls by open circles. Semi-closed circles mean that plots for both sexes are superimposed due to the scale of y-axis.
Fig. 5. Means for A-P and S-VX (mm) for boys and girls. Boys are represented by closed circles, and girls by open circles.

Fig. 6. Means for $\angle N-S-BA$, $\angle S-N-A$ and $\angle N-S-PNS$ (degrees) for boys and girls. Boys are represented by closed circles, and girls by open circles. Semi-closed circles mean that plots for both sexes are superimposed due to the scale of y-axis.
Cranial Base and Vault Dimensions

for girls.

The angle N-S-BA decreases with age until 18 years in each sex (Tables 1 and 2; Fig. 6). A linear trend to decrease is statistically significant for each sex at the 0.01 level for the first age group (0-3 years). The other trends are not significant except that for boys in the third age group (7-18 years) at the 0.05 level. The angle S-N-A decreases until the age of 10 years in boys and 9 years in girls; at older ages there are increases with age in each sex (Tables 1 and 2; Fig. 6). The level of significance in regression analysis towards a decrease in this angle is 0.01 for each sex in the period from 0 to 3 years. A tendency to decrease in the second age group and a tendency to increase in the third age group are not significant in either sex. This angle is greater in girls than in boys during the age range considered (Tables 1 and 2; Fig. 6). The angle N-S-PNS increases constantly with age in each age group for each sex. By regression analysis, the level of significance is 0.01 for each sex. For each age group, the sex differences between the means are small (Tables 1 and 2; Fig. 6).

DISCUSSION

The craniofacial skeleton can be considered to be composed of two bones: the cranio-maxillary complex and mandible (COBEN, 1961). Since the cranial base is the junctional region between the cranium and the face, there is interest in the growth of each individual part of the cranial base.

SCOTT (1958) suggested that the growth of the cranial base could be studied by dividing it into three segments: anteriorly, from nasion to foramen caecum; centrally, from foramen caecum to the pituitary point and posteriorly, from pituitary point to basion. However, these points cannot always be observed or anatomically determined on radiographs. KNOTT (1969, 1971), in her studies of serial age changes based on lateral radiographs, employed three segments for the anterior cranial base (sinus segment, ethmoidal segment, and presphenoid segment), and one for the posterior cranial base (post-sphenoid segment; MEREDITH, 1959). Descriptions of growth in the cranial base will be more informative if considered in relation to growth sites as enumerated by FORD (1958); i.e., sphen-occipital synchondrosis; spheno-mesethmoid synchondrosis; cartilage between mesethmoid and frontal bones, and in the frontal bone itself. The cranial base distances measured in the present study can be interpreted in relation to growth at these sites, but they reflect other changes also, for example, apposition at N, and BA and relocation of S. The endocranial points (VX, A and P) reflect endocranial resorption and relocation of the bones of the cranial vault.

The present results show N-S increases in each sex during the age range studied. These increases are due to elongation of both N-SE' and SE'-S, particularly N-SE' (Fig. 3). After closure of the sphen-ethmoidal suture, approximately at the age of seven years, further increases in
N-S are mainly contributed by the frontal bone (Björk, 1955; Grossman and Zucker-
man, 1955; Scott, 1958; and Stramrud, 1959). This bone increases in thickness in the region of N from birth to adult-
hood (Roche, 1953; Björk, 1955; Stramrud, 1959); most of this increase is accounted for by enlargement of the frontal sinus. The "bone thickness only" (or the thick-
ness of bone substance in the endocranial and ectocranial plates) during childhood and adolescence is approximately the same as during the first year of life (Roche, 1953).

After closure of the sphenoethmoid synchondrosis, the presphenoid length (SE′-S) continues to elongate. The mean incre-
ment from 7 to 18 years of age is approxi-
mately 1 mm for males and 0.8 mm for females. This increase is statistically significant at the 0.01 level for each sex. The probable mechanism underlying the increases in SE′-S is repositioning of S (Latham, 1972), and, perhaps, apposition on the anterior aspects of the greater wing of the sphenoid.

The present data concerning growth of the posterior cranial base show that mean values for S-BA increase with age. The annual increments between means are larger until 3 years of age than at older ages when the differences between successive means are close to constant, as described by many authors (Brodie, 1941, 1953; Grossman and Zuckerman, 1955; Stramrud, 1959; Fig. 2). However, analyses of serial data show pubescent spurts (Lewis and Roche, 1972, 1974; Roche and Lewis, 1974).

The increase in posterior cranial base length is ascribed primarily to growth activity at the spheno-occipital synchondrosis. The age of obliteration at this junction is about 13 to 16 years in boys and 11 to 14 years in girls by lamina-
graphy (Powell and Brodie, 1963), and 13 to 18 years in boys and 12 to 16 years in girls by autopsy and serial sections (Melsen, 1972). The results of Irwin (1960) are in the same range. Elongation of the posterior cranial base (S-BA) after the closure of sphenooroccipital synchondrosis is observed in this study as reported by Brodie (1941, 1953), Stramrud (1959), Lewis and Roche (1972, 1974), and Roche and Lewis (1974). Nevertheless, increases are not detected from 15 to 22 years in cross-sectional data (Koski, 1960). The differences between successive means become zero at 17 years in boys, and 15 years in girls (Melsen, 1969). This approximates the age at which growth ceases and is in agreement with an estimate of 16.1 years in girls from serial data (Bambha, 1961).

It is important to consider which of the two segments, basioccipital or basi-
sphenoid, is responsible for the elongation of the posterior cranial base. Cross-sec-
tional measurements were reported by Latham (1972) for 12 specimens (full-
term birth to 18 years) of the posterior cranial base in radiographs. These meas-
urements are from BA to the midpoint of the occipital border of spheno-occipital synchondrosis and the distance from S to the sphenoid side of the synchondrosis. The basiocciput increased steadily in
length from birth onward, showing an almost twofold increase in the oldest specimen. The distance from sella to the sphenoid-occipital synchondrosis increased until the age of 6 months and changed little after that (10.5 mm to 13.5 mm with a mean of 11.2 mm). The distance from the posterior wall of the pituitary fossa to the sphenoid-occipital synchondrosis increased until the age of 6 months and then was approximately constant (7.0 mm to 9.0 mm with a mean of 7.7 mm). In short, the basioccipital size increased throughout the age covered; however, the basisphenoid length remained almost unchanged after 6 months of age. Similar data were reported by Brodie (1941) and McNell (1962) for the distance from S to the synchondrosis. They considered this indicated reduced growth activity at the sphenoid-occipital synchondrosis, S being regarded as a fixed point.

Once an area of the synchondrosis is closed no further growth can take place at this site (Prichard, Scott and Girgis, 1956). The length of the posterior cranial base, however, increases slowly, but constantly, until early adulthood (17 years) in this study as well as other serial analyses of data from The Fels Longitudinal Study (Lewis and Roche, 1972, 1974; Roche and Lewis, 1974). Both the basioccipital length, and the basisphenoid length increase up to the time of obliteration of the sphenoid-occipital synchondrosis in each sex in the present study. Contrary to the findings of Latham (1972), the basisphenoid length does not remain the same size as in early childhood. Furthermore, the growth rate expressed as:

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\frac{(15 \text{ year length} - \text{birth size})}{15 \text{ year length}} \times 100
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is greater for S-SO' than for SO'-BA in each sex from 0-15 years. After the cessation of growth at the sphenoid-occipital synchondrosis, continuing elongation of the basisphenoid length can be credited to the upward and perhaps forward repositioning at S, and basioccipital elongation by apposition at BA (Powell and Brodie, 1963).

Concerning the growth in endocranial vault size, A-P length increases steadily over all age ranges, however, no significant increase in S-VX is observed in the third age group (7-18 years). The upward repositioning of sella point (Enlow, 1968; Meelsen, 1974) might have a negative influence on the expansion of the dimension.

The cranial base is a site of adjustment in growth between the neuro- and the viscerocrania (Björk, 1955; Scott, 1958; Ford, 1958). Many angles measured on radiographs of the cranio-facial region have been used in orthodontic practice to assist diagnosis, case assessment, and treatment planning. Nevertheless, the behavior of these angles during postnatal growth is controversial.

There is general agreement that the saddle angle (N-S-BA) is stable following the initial decrease after birth (Ortiz and Brodie, 1949; Brodie, Jr., 1955; Grossman and Zuckerman, 1955; Ochi, et al., 1974; Lewis and Roche, 1977 and George, 1978). Authors differ, however, in regard to the duration of the period after birth during which the angle decreases (3 months, Ortiz and Brodie, 1949; 1 year, 9
months, George, 1978; 2 years, Lewis and Roche, 1977). A slight decrease of the saddle angle from 7 years to adulthood was observed also in a cross-sectional sample (Koski, 1960). However, there is no significant tendency for the angle to decrease with age in cross-sectional data for Danish males from 3 to 15 years of age (Stramrud, 1959). Age-change studies are more reliable when based on longitudinal samples. In the present data, this angle decreases from birth to 2 years in each sex. After two years this angle does not remain constant, but the changes are small. By regression analysis, these age changes are statistically significant from 0-3 years at the 0.01 level in each sex. Also the changes from 7-18 years are significant for boys (0.05 level), but not for girls.

The distribution of the angle S-N-A in patients and normal persons has been investigated (Downs, 1948, 1952; Walker and Kowalski, 1972a, b). A mean value of 81 degrees (78°-84°) was found in persons with clinically "excellent occlusions" aged from 12 to 17 years and equally divided with respect to sex (Downs, 1948). In data from children and young adults also with normal dental occlusion, little sexual dimorphism is evident and there is a slight but definite tendency for this angle to increase with age. Results from other authors are in general agreement with these findings (Steiner, 1953, 1959; Walker et al., 1971, 1973, Järvinen, 1980). In the present study, means for the angle S-N-A change little after 1 year in boys and 2 years in girls but there are slight decreases until 10 years in boys and 9 years in girls after which there are slight increases with age. The early phase of decreases in this angle may be associated with the forward and upward repositioning of the anterior cranial base; the final phase of increases may reflect pubescent growth in facial depth.

Final conclusions have not been reached concerning the repositioning of N with age in relation to S and BA. The stability of the N-S line (NSL) in relation to the median contour of the anterior cranial fossa has been investigated by measuring the perpendicular distances from NSL to ethmoidale (cribriform plate) and to the uppermost point of the orbital cavity. NSL remains in a rather stable position relative to the anterior cranial fossa from 3 years of age to maturity in cross-sectional data (Stramrud, 1959). Similarly, in serial radiographic data, Björk (1955) found this line remains constant in relation to the deepest median contour of the anterior cranial fossa from 12 to 20 years of age in Swedish males. In cephalometric analyses, NSL is frequently applied as the reference line for the anterior cranial base (Brodie, 1941; Björk, 1947, 1955; Lindegård, 1953, and Ricketts, 1955). The use of this line is, however, arbitrary as it is well known that there are no fixed points or areas in the cranium during growth (Baume, 1957).

Changes in angular relationships, that may be caused by the different growth rates and directions of growth among cranio-facial linear dimensions, are apparent in the present data. The angle N-S-
BA tends to decrease gradually subsequent to the initial decreases after birth and angle N-S-PNS increases throughout the age range studied. There are two phases in the growth changes observed in the angle S-N-A: a period of decrease until pubescence, followed by a period of increase.

The appropriate way to investigate the relationships among several landmarks over age is to register them in a coordinate system. From the behavior of distances and angles, however, some inference may be possible concerning the relocation of these landmarks; decreases before pubescence in the angle S-N-A support the view that N moves upward during its forward growth (KEITH and CAMPION, 1920, and increases after pubescence indicate that Point A moves forward more than does N. A tendency for angle N-S-BA to decrease suggests that the clivus is becoming relatively more upright (LA-THAM, 1972).

In this connection, some calculations were made from the data of KOSKI (1960) by the present authors. In his study of 331 lateral radiographs of the head taken of children and students from 6 to 31 years of age, the points N, S and BA were projected perpendicularly onto the HIS' line (HIS, 1876) as N', S' and BA', respectively. The HIS' line from acanthion (anterior nasal spine) to opisthion (most posterior point on the margin of the foramen magnum), was reintroduced by KOSKI (1953) as a reference line that would connect the cranial base area with the face.

First, the ratio of N-N' to S-S' was obtained from the mean values for each age group. In each sex, this ratio tends to increase with age. The vertical repositioning with age or upward growth in relation to HIS' line is greater at N than at S.

Secondly, the ratio S-S' to BA'-S' was calculated for each age group in each sex to determine the direction of repositioning at S during growth. In other words, vertical and horizontal movement of S was checked. Increases in the ratios with advancing age were again noticeable in each sex. This suggests that the clival inclination becomes steeper with age (MELEN, 1974).

During the course of growth, the rate of increase for each dimension in the cranial base is different. Moreover, the direction of growth for these dimensions causes changes in the shape of the cranial base. There seems to be no fixed points and/or areas in the cranium during growth as suggested by BAUME (1957). According to a factor analysis of the cranial base and vault size in children (OHTSUKI, MUKHERJEE, LEWIS and ROCHE, 1981), each segment, i.e., frontoethmoidal, presphenoid, basisphenoid and basioccipital, is associated separately in a different component for the three-year age groups (4-6, 7-9, 10-12 and 13-15 years). These results may suggest that each cranial segment has its own growth pattern. Furthermore, changes in factor patterns are reported to be consistent with the ages at which changes in growth rates or growth patterns may appear, i.e., around the ages of 3, 6 to 7, and 15 years, and around the
ages of 3, 6 to 7, and 13 years in girls. Perhaps differential growth rates among cranial base dimensions cause changes in factor patterns.

A vigorous growth activity in the cranial components for several years after birth is not followed by a quiescent period of growth activity. Even though later age changes are small, biological events are still continuing until after pubescence. Pubescent spurts in some cranial base dimensions are also observed similar to those in other body dimensions (Lewis and Roche, 1972, 1974; Roche and Lewis, 1974).

Although many cranial data have been accumulated thus far, the cranio-facial region will still remain a topic of great concern for physical anthropologists and orthodontists. The present study, which is based on mixed longitudinal data from a large sample, will provide a better understanding of growth in the cranial base and cranial vault; studies of changes of growth patterns in the cranial region for individuals will be brought into focus. The data may be used later to predict some dimensions and angles in the cranio-facial region that will be helpful to clinicians.

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頭蓋底と頭蓋冠の諸測度の加齢的変化について

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Felsの縦断形の発育研究の参加者（0〜18才の男子220名，女子177名）を対象とした頭部側面X線フィルム（男子1861，女子1401）を用いて，頭蓋底と頭蓋冠の諸測度を計測した。
この研究に用いた頭蓋底の測度は次の通りである：craniab base (nasion-basion); anterior cranial base (nasion-sella), fronto-ethmoidal segment (nasion-sphenoethmoidale), presphenoid segment (sphenoethmoidale-sella); posterior cranial base (sella-basion), basisphenoid segment (sella-sphenooccipital), basioccipital segment (sphenooccipital-basion). 頭蓋冠については全て内外頭蓋点を用い，頭蓋最大高 (sella-vertex) と頭蓋最大長 (anterior-posterior) を計測した。その他頭蓋底の発育の相対的な方向を知るために，次の角度を測定した：nasion-sella-basion, sella-nasion-point A, nasion-sella-posterior nasal spine.

各測度について，平均値の年齢的変化を性別に記述した。統計学的な有意性の検定には，全資料を3つの年齢群（0〜3, 4〜6, 7〜18才）に分けた後，それぞれの群内で性別に回帰分析を行った。なお，この年齢区分は頭蓋底の軟骨結合部の約その発育が進行した時期を示すのと同様の意義を有していると考えられる（OHTSUKI, MUKHERJEE, LEWIS and ROCHE, 1981）。

従来の結果と相違するものとしては，男女とも斜台 clivus の発育にさいし，basisphenoid と basioccipital の両部分がともに寄与していることである。また，∠SNA は男子において10才，女子においては9才まで減少するが，その後に増加の傾向を示す。その他，nasion, sella および basion 三者の相対的な位置関係の加齢的変化については，従来，必ずしも一致した見解を得ていないが，nasion は発育の過程において，前上方に位置を移し clivus の傾斜はより強くなることがわかった。