Growth in the external cranial base evaluated on human dry skulls, using nerve canal openings as references

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The purpose of this investigation was to measure on human dry skulls the postnatal widening and lengthening of the external cranial base, including the hard palate, using nerve canal openings as references. Forty-five Indian dry skulls were examined, 36 from children and 9 from adults. The age evaluation was made on the basis of dental development. The dimensions of the external cranial base were determined by direct measurements on the skulls and by measurements from photographs of the skulls. The study showed that growth in width of the external cranial base followed two distinct patterns. The two regions represent different embryologic developmental fields. The study points out that different growth patterns in these fields ought to be taken into account in future investigations of normal and pathologic craniofacial growth. □ *Development; mandibular fossa; palatine foramen; spinous foramen; stylomastoid foramen*

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Although the human cranium is relatively large at birth, it undergoes considerable dimensional changes before reaching its final size in adult life.

Longitudinal cephalometric studies have been carried out on growing children on the basis of profile radiographs (1, 2). The implant method introduced by Björk (3), in which stable reference points in the form of titanium pins were implanted in the cranial bones of growing children, has increased the insight into craniofacial growth (4). These studies showed that the angle of the cranial base, the sella–nasion–basion, is close to constant (131°) under normal growth conditions. Longitudinal studies of growth in the horizontal plane are scarce (5), mainly because of practical difficulties in the radiologic procedure. Implant insertion in this part of the skull has not been possible. In children with craniofacial malformations it has been possible to take radiographs in the submentovertex projection while the children were anesthetized for operation (6).

On skeletal material cross-sectional studies of the development of the cranial base have been made on the basis of profile radiographs. One study showed that the structures of the anterior cranial fossa seem to have a stable medial part and a more unstable lateral part (7). Melsen (8) observed in another study that the spheno-occipital synchondroses close from the internal side at the age corresponding to eruption of the second molars. Vinkka & Koski (9) observed an unchanging cranial area within the cranial base.

Histologic studies of postnatal growth in the cranial base on the basis of human autopsy material have been conducted by Thilander & Ingervall (10) and Melsen (11). These studies show that closure of the spheno-occipital synchondroses takes place between 13 and 19 years of age.

Several authors have performed antropometric measurements on skeletal material. It has been claimed that the distance from the sella turcica to the foramen magnum does not increase after the age corresponding to eruption of the first permanent molar (12). Certain areas of the cranial base follow either the neural or the general skeletal pattern of growth (13). It has been stated that there might be a functional relation between the neurovascular canals of the jaws and the occlusion (14). A combined macroscopic/microscopic study of dry skulls and autopsy material showed that the pterygopalatomaxillary region is a border area between two different growth patterns; that of the pterygoid process is part of the cranial base, which stabilizes at an early age, and that of the maxilla follows the growth pattern of the body with periodic variations (15). A relationship between nerve tissue growth and bone growth in the craniofacial skeleton has been suggested (16). Relative growth of the skull base using such anatomic landmarks as the neuro- and cardio-vascular canals has been studied (17, 18). A recent investigation of growth in the maxilla in the horizontal plane has shown that nerve canal openings can be used as reference points for patterns of growth in length and width of the palate (19). That study showed that the growth in length of the palate takes place mainly anterior to the greater palatine foramina and that a continued growth in width occurred also in adult life (19). The study confirmed the results of cephalometric analyses of maxillary growth in children (3, 20).

Embryologic studies of cranial base development (21) have shown that there are developmental fields with different origins in the cranial base. One field border is located in the sella turcica area, which means that some malformations are seen posterior to the sella turcica (22) and others are seen anterior to it (23).

The purpose of the present study was to investigate the external cranial base, focusing on different growth patterns demonstrating different developmental origin of the regions.

Materials and methods

Materials

The cranial material used in this study derives from Calcutta, India. The 45 crania, 36 of which are from children and 9 from adults, form part of Arne Björk's Skull Collection, which belongs to the Department of Orthodontics, School of Dentistry, University of Copenhagen. The crania showed no signs of general disease. The skulls are therefore considered to constitute a normal sample. Sex determination of the crania was not possible owing to the many immature individuals in the collection.

Methods

Age evaluation. The age determination of the crania was carried out on the basis of dental development as defined by Björk et al. (24). Dental stage (DS)01 = deciduous teeth erupting (not yet in occlusion), DS02 = deciduous teeth completely erupted (in occlusion), DS1 = permanent incisors erupting, DS2 = permanent incisors completely erupted, DS3 = canines and premolars erupting, DS4 = canines and premolars completely erupted, DSM1 = first permanent molar completely erupted, DSM2 = second permanent molar completely erupted, DSM3 = third permanent molar completely erupted. According to Helm & Seidler (25), average ages of eruption of the permanent teeth are as follows: DS1, 6 years; DS2, 8–8.5 years; DS3, 9–9.5 years; DS4, 12–12.5 years; DSM1, 6 years; DSM2, 13–13.5 years.

In the present material all dental stages were represented, with the exception of DS01. Individuals with mixed dentitions belonging to DS1, DS2, DS3 combined with DSM1 (6–9.5 years) were regarded as one group, as each of these dental stages consisted of relatively few individuals. The material thus consisted of four groups: 1) complete deciduous dentition (DS02); 2) mixed dentition (DS1, DS1M1, DS2M1, DS3M1); 3) permanent dentition exclusive of the third molar (DS4M2); 4) complete permanent dentition (DS4M3). A few crania, which in skeletal age belonged to DS4M3, were classified as DS4M2 because of agenesis or impaction of the third molar.

Helm & Seidler (25) have recorded sex differences in eruption rates and found that girls are up to 1 year in advance of boys. The sex differences have not been taken into account in this study owing to the difficulties of determing the sex on such material.

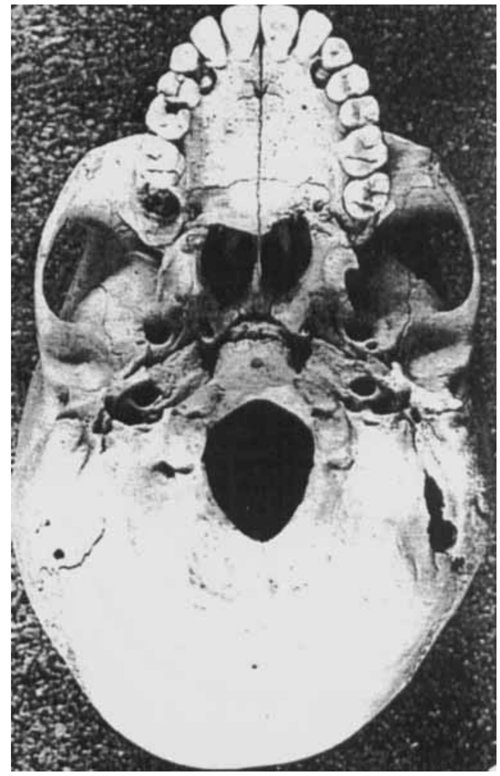

Fig. 1. Photograph of a human cranium seen from below. The dental development, stage DS3M2, corresponds to an approximate age of 13 years.

Measurements of the cranial base. On each cranium three measurements of width (Figs. 2 and 3) and three of length (Fig. 4) were made on the external cranial base. The distances were measured between the nerve canal openings. In addition, a reference point was constructed in the mandibular fossa for the purpose of measuring the width in this area. Moreover, the distance between the mandibular fossa and the greater palatine foramen was recorded. The three width measurements, between bilateral nerve canal openings, were made directly on the cranium using a slide caliper (0.01–150 mm; Mitutoyo Corp. Digimatic) (26).

To make it practically possible to undertake width measurements between the mandibular fossae and length measurements of cranial structures on different horizontal levels, all the external cranial bases were photographed. The crania were placed in a box of sand and oriented with the occlusal plane of the maxilla horizontal. This was done in practice by using a spirit level, resting on a Plexiglass plate, placed on the occlusal plane of the teeth, both in the anterioposterior direction and in the mediolateral direction. The photographs were taken with an Olympus OM-2N camera in a fixed position on Kodak TMX 100 ASA film, routinely processed (Fig. 1). Paper prints were

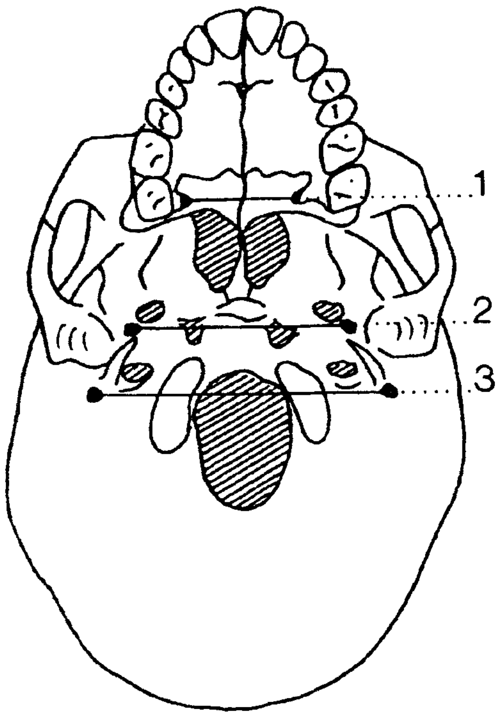

Fig. 2. Sketch of a human external cranial base illustrating the width measurements between nerve foramina. 1 = interpalatine width, 2 = interspinous width, 3 = interstylomastoid width.

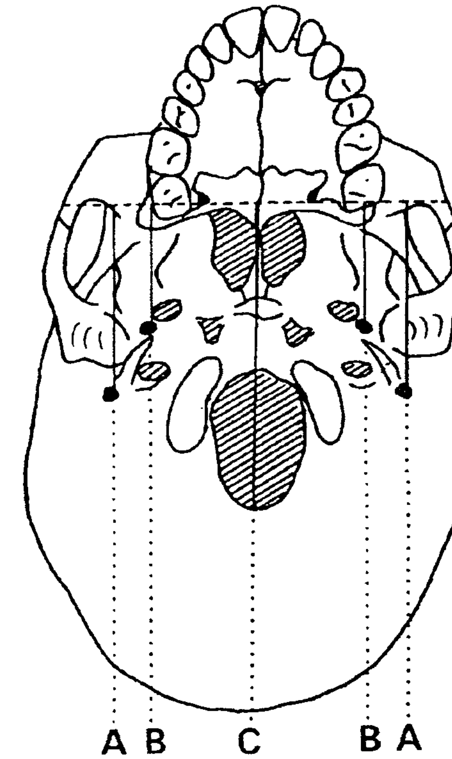

Fig. 4. Sketch of a human external cranial base illustrating the length measurements between nerve foramina. A: stylomastoid foramen length. B: spinous foramen length. C: cranial base length.

produced, and all the measurements were made using Mitutoyo type 505-666, D15F slide calipers.

Direct skull measurements. 1. Interpalatine width: the distance between the medial edges of the left and right greater palatine foramina (Fig. 2).

2. Interstylomastoid width: the distance between the medial edges of the left and right stylomastoid foramina (Fig. 2).

3. Interspinous width: the distance between the medial edges of the left and right spinous foramina (Fig. 2).

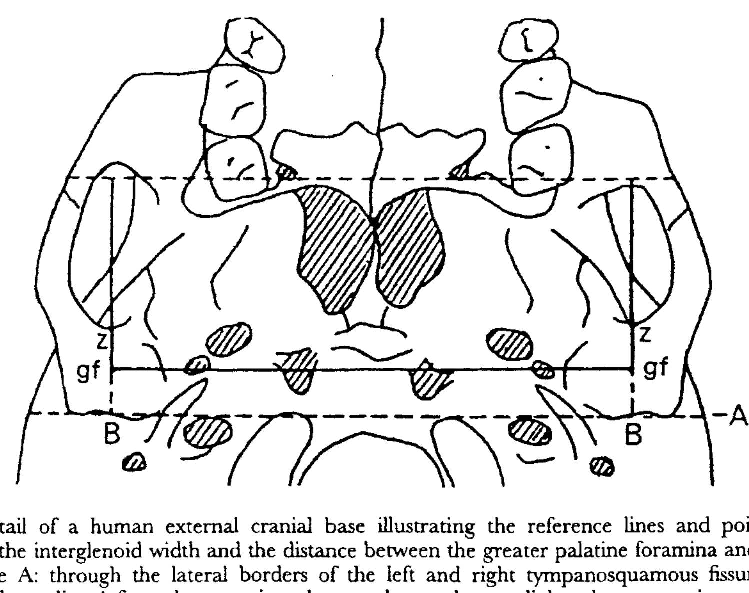

Fig. 3. Detail of a human external cranial base illustrating the reference lines and points used for measuring the interglenoid width and the distance between the greater palatine foramina and the glenoid fossae. Line A: through the lateral borders of the left and right tympanosquamous fissures. Lines B: perpendicular to line A from the posterior edges on the notches medial to the zygomatic processes on the temporal bones, points z. Points gf (glenoid fossae): midpoints on that part of the B lines connecting points z with line A.

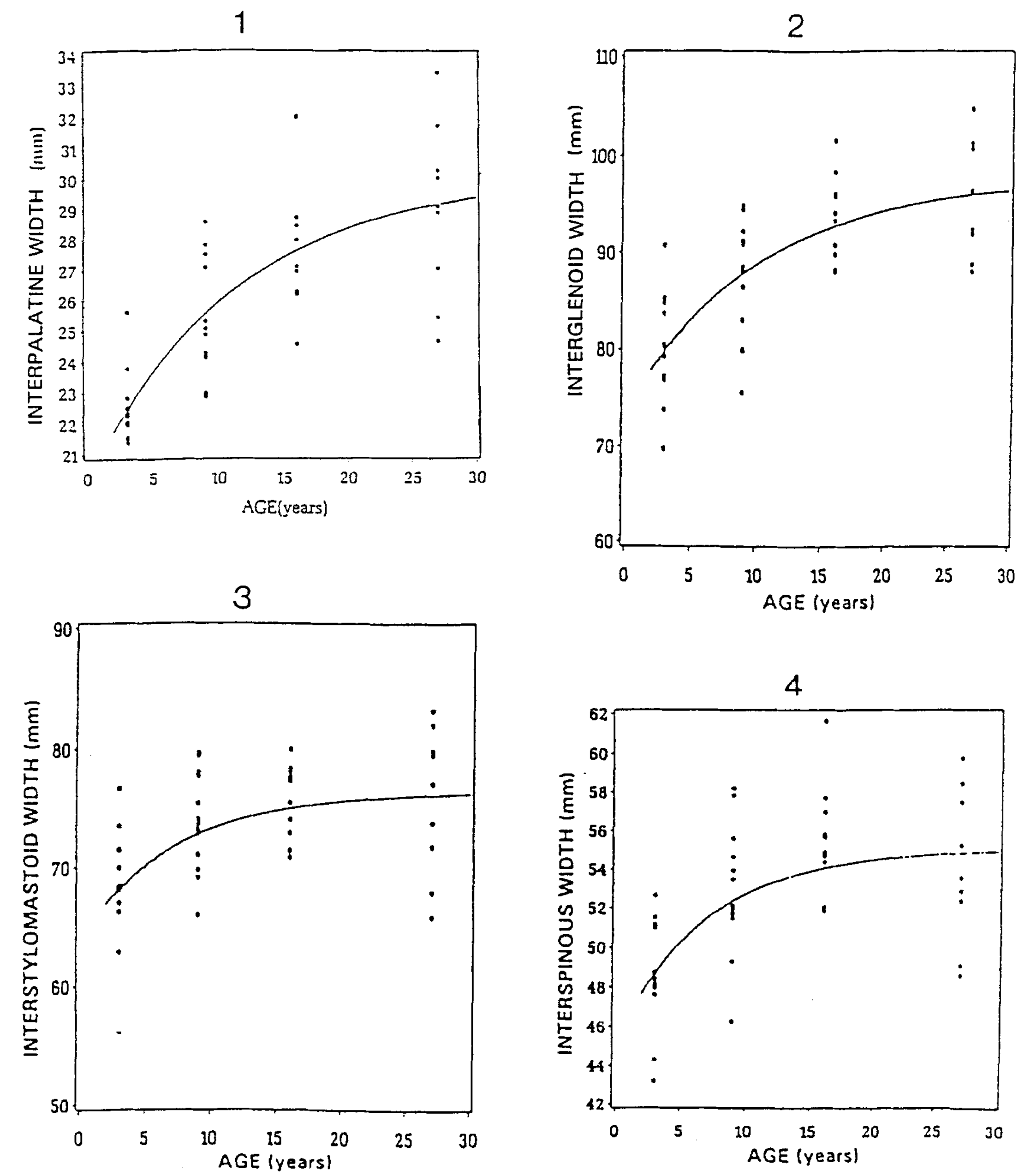

Fig. 5. Width measurements of the external cranial base. 1. The interpalatine width showed a linear increasing course with increasing age. 2. The interglenoid width showed an increasing course, with increasing age. 3 and 4. The interstylomastoid width and the interspinous width both showed a significant difference between dental group 1, corresponding to an age of about 4 years, and the other dental groups.

Photo measurements. 4. Interglenoid fossa width: line A connects the lateral borders of the left and right tympanosquamous fissures. Two perpendicular lines B are drawn through the posterior edges on the notches medial to the zygomatic process on the temporal bones. The distance between the B lines thus indicates the width (Fig. 3).

5. The length from the greater palatine foramen to the spinous foramen: the distance between the posterior edges of the greater palatine foramina and the left and right spinous foramina (Fig. 4).

6. The length from the greater palatine foramen to the stylomastoid foramen: the distance between the posterior edges of the greater palatine foramina and the left and right stylomastoid foramina (Fig. 4).

7. Cranial base length: the distance between the posterior edges of the greater palatine foramina and the great occipital foramen (Fig. 4).

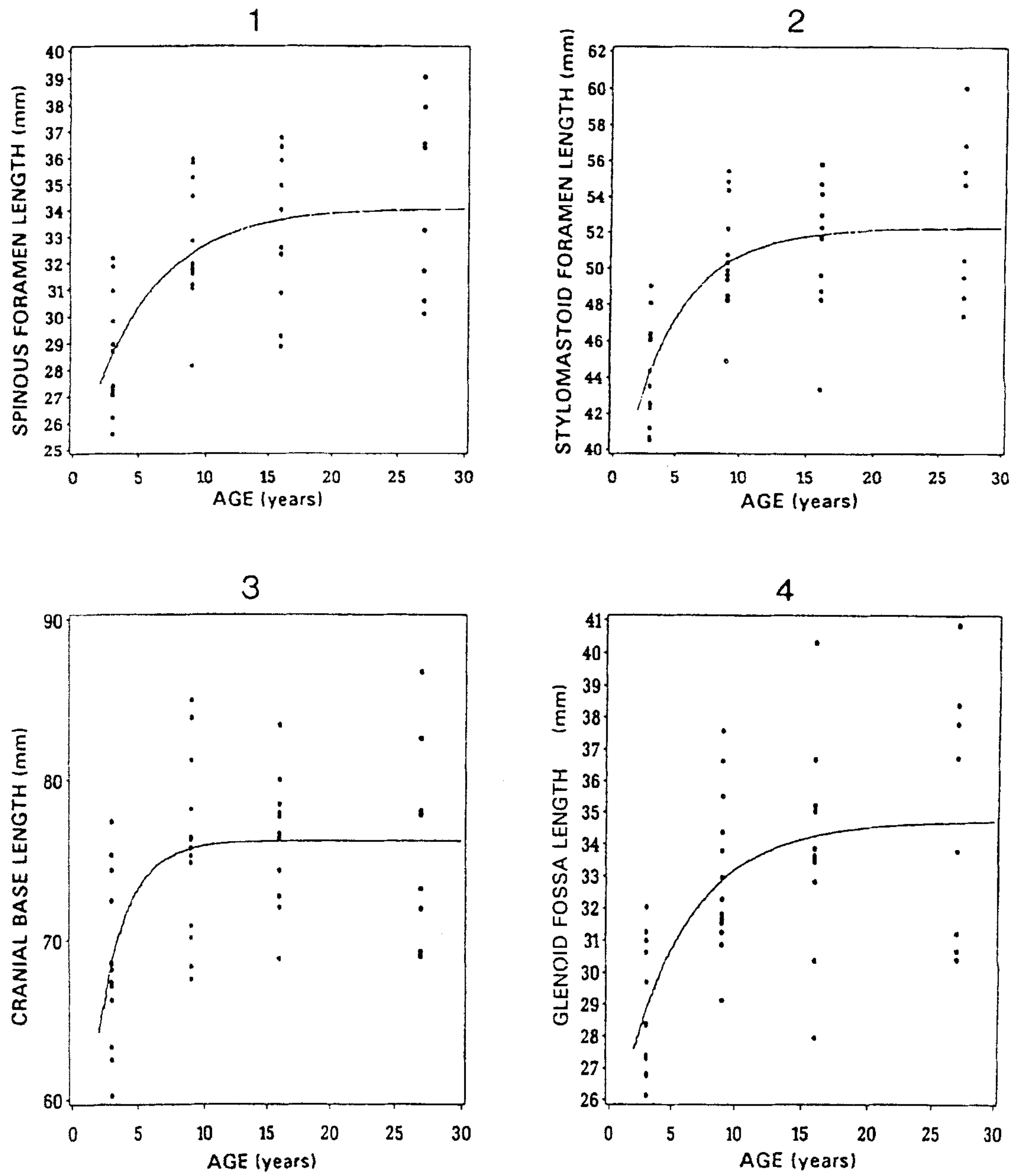

Fig. 6. Length measurements of the external cranial base. Spinous foramen length (1), stylomastoid foramen length (2), cranial base length (3), and glenoid fossa length (4) all showed a significant difference between dental group 1, corresponding to an age of about 4 years, and the other dental groups.

8. The length from the greater palatine foramen to the glenoid fossa: the distance between the posterior edges of the greater palatine foramina and the midpoint on lines B (points FM) (Fig. 3).

For all the length measurements included in the study, a mean value was calculated on the basis of measurements from both the left and right sides of the cranium. These mean values vere used for further calculation. On some of the skulls it was not possible to register all eight measurements due to local fractures of the bone; as a result, the total number of measurements varies between 38 and 43 within each group.

Reliability of measurements. To obtain exact values for the distances, it was necessary, because of the different levels in the individual cranial regions, to use local conversion factors on the basis of the direct cranial measurements in the actual area. Three conversion factors were calculated for each individual; the interpalatine factor, the inter-stylomastoid factor, and the interspinous factor. The conversion factor is the ratio between the distance measured on the skull and the same distance measured on the photo. The exact value of the interglenoid width was calculated from the photo measurement times the factor related to the interspinous width, as these structures are located close to each other.

For the length measurements the distance between the two points were in different levels, and it was therefore necessary to use a combined factor. The length from the greater palatine foramen (representing the upper level) to the spinous foramen (representing the lower level) was accordingly converted by using a factor representing the mean of the interpalatal and interspinous factors. The length from the greater palatine foramen to the stylomastoid foramen was converted by using a factor representing the mean of the interpalatal and interstylomastoid factors. The length from the greater palatine foramen to the great occipital foramen was converted by using a factor representing the mean of the interpalatal and interstylomastoid factor (which is the nearest factor). The length from the greater palatine foramen to the mandibular fossa was converted by using a factor representing the mean factor of the interpalatal and interspinous factor (which is the nearest factor).

All the length measurements are performed parallel to the median axis of the cranial base. It was therefore possible to compare these measurements with the measurements taken from lateral radiographs used in cephalometry. However, this method does not take small asymmetries of the cranial base into account.

Statistical evaluation. To characterize the width and length measurements from the external cranial base in relation to the dental groups, the procedure was as follows: for each dental group a mean age was assigned for further calculations. Rather than making simple comparisons of successive age groups, the pattern of growth was described by a flexible three-parameter family of functions, defined as:

$$h(\text{age}) = a_0 + (a_{\text{adult}} - a_0)\,(1-\exp(-r\ \text{age})),$$

where a_0, a_{adult}, and r are unknown parameters, different for each measurement, interpreted as follows: a_0 = cut-off on the y-axis—that is, the value for age 0; a_{adult} = asymptote—that is, the adult value; r = the measure of curvature (growth rate) (27). For each measurement the parameters were estimated by the least-squares method, ignoring uncertainty in the age determination. $P < 0.05$ was considered to be statistically significant.

Results

The dimensions of the external cranial base, related to increasing age, showed the following:

Growth in width

The measurements of the palatal width showed continuing growth increments in the dental groups (age groups) studied (Fig. 5). The measurement of the distance between the glenoid fossae likewise showed an increase as the dental age increased (Fig. 5). The measurements of the distance between the stylomastoid foraminae and the distance between the spinous foraminae showed a significant difference between dental group 1 (corresponding to a complete deciduous dentition and a mean age of about 4 years) and the other dental groups (Fig. 5).

Growth in length

All four cranial length measurements (Fig. 6) showed a significant difference between dental group 1 (corresponding to a complete deciduous dentition and a mean age of about 4 years) and the other dental groups. The distinction in two patterns was not seen in the growth in length. Statistical evaluation of the estimated parameters is shown in Table 1.

The estimated parameters for the interpalatal width (INPALW) showed an intercept level at 22.3, and the slope was 0.3.

Discussion

In the present investigation dimensions in the external cranial base on Indian dry skulls were measured and evaluated on the basis of growth patterns. As these studies are based on cranial material, the investigation is naturally of a cross-sectional nature. In this work the term 'growth' is therefore used for the dimensional changes registered in the cranial base during development from the primary to the permanent dentition. The age determination of the individuals was based on dental development. According to Nanda & Chawla (28), dental development among Indian children is delayed in comparison with American children (29, 30).

In the present study two interesting growth patterns emerged. The first pattern was characterized by a strong growth intensity of the cranial base up to the age of 4–5 years, followed by diminishing growth and, at last, growth

Table 1. Estimated parameters for width and length measurements

Variable	a_0	a_{adult}	r
INCONW	73.5	97.6	0.1
INSTYW	63.9	76.5	0.1
INSPIW	45.2	55.1	0.2
SPIFLG	24.4	34.1	0.2
STYFLG	36.1	52.2	0.2
CRBALG	46.5	76.2	0.5
GLFOLG	24.2	34.8	0.2

INCONW = intercondylar width; INSTYW = interstylomastoid width; NSPW = interspinous width; SPIFLG = spinous foramen length; STYFLG = stylomastoid foramen length; CRBALG = cranial base length; GLFOLG = glenoid fossa length; a_0 = level at age 0; a_{adult} = estimated value at adult age; r = rate of approaching asymptote.

arrest. This pattern has earlier been described by Friede (31) and Hoyte (5). Lang & Issing (17) carried out similar studies, and the values obtained in the present report accord well with their findings. The spinal cord and many blood vessels and cranial nerves penetrate this part of the cranium. These structures form early in fetal life and seem to maintain their relative distance to one another during the development of the external cranial base (32). The great occipital foramen is already nearly adult in size when the intraoccipital synchondroses have ossified in early childhood (5, 31, 33).

The second pattern relates to the growth in width of the maxilla, expressed by the distance between the left and right greater palatine foramina. This width increased seemingly after the age at which growth is generally expected to have ceased. In this study postpubertal age is considered the age after DS4M2. The palatal growth pattern shown is in agreement with the results of a similar study undertaken on a Danish cranial material (19). However, caution must be exercised when interpreting cross-sectional data. Björk (1) found, in growing children, that the growth occurring in the median palatine suture is differential, so that the greatest width increase occurs in the posterior part of the palate.

The same pattern was in the present study recorded for the width increment of the intercondylar fossa (as an expression of the width increment of the mandible), which likewise increases continuously. Continuous growth has earlier been observed in the mandible by Baumrind & Korn (34), who with the aid of metal implants found that there is a small but measurable increase in width in the mandible, which continues into adult life after growth has apparently ceased in the symphysis menti. Israel (35), in a longitudinal radiographic study, found that the widening of the skull during adult life happened at a rate per unit time which is twice the rate of the widening of the anterior-posterior skull diameter. Ruff (36) found a continuing adult craniofacial expansion in a skeletal material from Indian Knoll, Kentucky, USA. It is reasonable to assume, as formerly stated by Sejrsen et al. (19), that in individuals with harmonious occlusion there is a correlation between the width increments in the maxilla and in the mandible, presumably influenced by the masticatory function.

Björk & Skieller (4) found, with the aid of the implant method, that the pterygopalatine fossa, the pterygopalatine canal, and the greater palatine foramen in the hard palate do not alter position anteroposteriorly in relation to the sella turcica during growth. In the sagittal plane a considerable increase in the length of the hard palate was found anterior to the greater palatine foramen, whereas the distance from the greater palatine foramen to the posterior margin of the palatine bone did not increase significantly during growth (19). Prenatal studies of growth in the hard palate evaluated on dry skull material have shown that differential growth occurs in the transverse palatine suture, as the maxillary part of the palate gained two-thirds and the palatinal part of the palate one-third of the total length during the second trimester (37). This growth pattern was identical with the pattern observed in postnatal skeletal material (19).

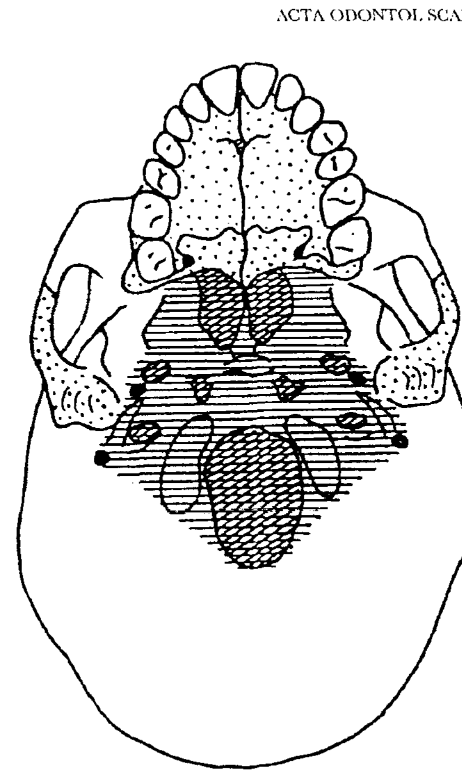

Fig. 7. Sketch of the human external cranial base. The hatched area indicates the central core, which expands in width and length during early childhood. The dotted area is the semilunar block in which continuous growth occurs.

The present study suggests that a non-expanding central area in the external cranial base has developed at about 4–5 years of age. This area is bordered by the spinous foramen, the stylomastoid foramen, and the great occipital foramen. Anterior and lateral to this core a semilunar block, containing the maxilla and the mandibular fossa, was found to expand in width onto DS4M2 (Fig. 7). Prenatally, the distance between the mandibular condyle and the anterior tympanic ring is stable during the second trimester (38). Postnatally, it is to be expected that both structures are found in the semilunar block.

In individuals with craniofacial malformation the cranial base is often malformed. Thus the length and width dimensions recorded in the cranial base of cleft palate patients differ from the dimensions measured in individuals with normal cranial development (6). Children with cleft palate have a broader external cranial base and a broader maxilla (6). In patients with craniosynostosis deformity of the cranial base has also been observeded (39). In cases of mandibulofacial dysostosis a shortening of the anterior and posterior parts of the cranial base is found (40). In fetuses with anencephaly malformations have been observeded in the basilar part of the occipital bone (41). As this part of the cranial base develops around the notochord, it is proposed that the core defined in the present investigation could be identical with that part of the cranial base developed from the parachordal mesoderm. The semilunar facial skeleton could be identical with the craniofacial skeleton developed from the neural crest. This part of the cranium was in prenatal analysis not nessesarily malformed in cases of malformations in the central core area (41, 42).

The present investigation shows that prenatal developmental borderlines might exist also in postnatal life. Borderlines between cranial fields with different developmental origins have formerly been described in dry skull material by Barnes (43).

The fact that there are various growth patterns in the different fields postnatally is a new observation that can be incorporated in a future charting of craniofacial malformations, studied both on children and on dry skull material. The results of the distances measured can serve as standards in future investigations of the cranial base and possibly as basic studies for measurements on computed tomography scanning and magnetic resonance scanning images.

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