Sex Differences in the Elongation of the Cranial Base During Pubescence

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This paper aims to delineate the sex differences in cranial base elongation during pubescence. Pubertal spurts in cranial base lengths have been demonstrated;[1,2] these vary in timing and intensity between individuals, as do pubertal spurts in other body dimensions. The comparisons that will be made between the sexes relate to the rates of elongation and the timing of pubertal spurts in the cranial base. These aspects of growth in this area will be considered in relation to sex differences in statural growth during puberty.

MATERIAL AND METHODS

The children studied, and the manner in which the raw data were obtained, have been described previously in detail.[1,2] The two samples of southwestern Ohio white children included fifty-eight boys and forty-one girls who were radiographed within one month of each birthday. The age range of the serial radiographs varied between children but extended from at least two years before to two years after peak height velocity (PHV).

On tracings of these radiographs, Ba-N, S-N and Ba-S were measured to the nearest 0.1 mm using Helios calipers; these distances were corrected for the known radiographic enlargement. As an operational procedure, spurts were considered present when an annual increment exceeded the immediately preceding increment by at least 0.75 mm/year in the boys and 0.5 mm/year in the girls. Different criteria were applied in each sex because the prepubertal rates of elongation were considerably greater in the boys than in the girls. The occurrence of multiple spurts in some children allowed analyses of "first pubertal spurts," which were the first to occur in the period from two years before to two years after PHV, and of "maximum spurts." A "maximum spurt" was defined as the largest increase between successive annual increments that satisfied the requirements of a spurt.

Other data recorded for these children included serial six-monthly statures (used to obtain the age of PHV), age at menarche, and six-monthly skeletal ages assessed using the Greulich-Pyle atlas[3] in a bone-specific manner. In addition, the age at onset of ossification of the ulnar sesamoid of the first metacarpophalangeal joint of the thumb (US) was noted.

The rates of elongation (mm/year) of each cranial base length have been described using the tenth, fiftieth (median) and ninetieth centiles because the data were skewed slightly at most ages. The distributions of these rates, of course, were truncated for later intervals when elongation had ceased in some children. Each graph (Figures 1-8) includes centile lines that were fitted by eye to the recorded points, taking into account the number of boys or girls for whom data were available for each age interval. In accordance with common practice these graphs will be interpreted and described as if the data were continuous across age. This provides a more accurate description of the changes in

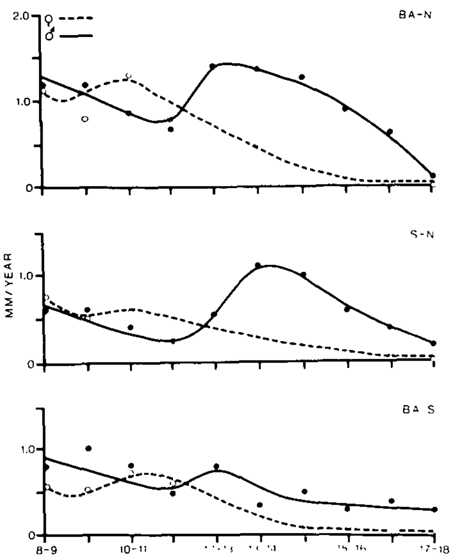

Fig. 1 Median increments (mm/year) in boys and girls for Ba-N, S-N and Ba-S.

rates that did occur than an account limited to the observed data points.

Findings

Rates of Elongation

The median rates of elongation for the three cranial base lengths (Ba-N, S-N and Ba-S) are shown in Figure 1.

In the boys the median rate of elongation of Ba-N decelerated from 8.5 to 11.5 years but then accelerated markedly until about 13 years; later it decelerated at an increasing rate. Due to the occurrence of pubertal spurts, the median rate from 12.3 to 14.0 years exceeded that at 8.5 years. In the girls the median rates changed similarly with age, but the pubertal spurts, as shown by increases in the rates of elongation, occurred about two years earlier than in boys. Due to this difference in timing, the lines for median elongation rates for the boys and girls intersected twice. The first intersection occurred at about 9.5 years when the rate of elongation became greater in girls; the second was at about 11.8 years when the median rate became less in girls. In girls the median rate of elongation decelerated to zero at 16.5 years but had not done so in the boys by 17.5 years, the last age for which data were available.

The median rates of elongation of S-N and Ba-S showed similar patterns of change to those of Ba-N. The rates for S-N and Ba-S decelerated from 8.5 years to 11.5 years in boys and from 8.5 to 9.5 years for girls. Subsequently, there were accelerations that continued until these medians reached their maximum values at about 12.5 to 13.5 years in boys and 10.5 years in girls. The median rate at the spurt was greater than at 8.5 years, in S-N for the boys and in Ba-S for girls. Again, the medians intersected at about ten and twelve years. The first intersections occurred when the girls median rates were accelerating and those for boys decelerating; this pattern was reversed at the time of the second intersection. In addition, the data in Figure 1 show differences between the sexes in the ages at which the median rates of elongation reached their maximum values. These were similar for all three lengths in the girls, but in boys the maximum rate for S-N occurred one year later than the maximum rates for Ba-N and Ba-S.

There are other striking sex differences in the median rates of elongation. The increases shown in Table 1 are from the lowest rate prior to the pubertal spurt to the maximum rate during the spurt, as determined from median rates of elongation (Fig. 1). The absolute changes (mm/year) for Ba-N and S-N were markedly greater in boys than in the girls, whereas the increase was similar in each sex for Ba-S. The sex difference in the absolute increases of S-N was striking; it was even more dramatic for the relative increases. In

TABLE I

Absolute (mm/year for Cranial Base Lengths; cm/year for Stature) and Relative (%) Increases in Median Rates of Elongation at Puberty and the Ages at Which the Median Rates Were Maximal

Length	*Absolute Increases*		*Relative Increases*		*Age at Maximum Rate*	
	Boys	*Girls*	*Boys*	*Girls*	*Boys*	*Girls*
Ba-N	0.65	0.25	84	25	12.8	10.3
S-N	0.85	0.05	340	9	13.7	10.5
Ba-S	0.20	0.25	45	53	12.6	10.7
Stature	2.75	1.50	56	28	13.5	11.5

the boys the maximum rate of elongation was more than three times the minimum rate before puberty, but in girls the maximum rate exceeded the minimum rate by only nine per cent. In Ba-N the relative increase was also markedly greater in the boys (84%) than in the girls (25%) but there was only a small sex difference between the relative increases for Ba-S.

The elongation of S-N from 9.5 to 17.5 years was about 2.4 mm greater in the boys than the girls (median values). Similarly, during the same age range, elongation in boys exceeded that for girls by 4.3 mm for B-N and by 2.2 mm for Ba-S. However, not all these sex differences in total increments from 9.5 to 17.5 years were due to the sex differences between pubertal spurts. The median rates of elongation in boys exceeded those in girls, at all ages, except during the short period when the girls experienced pubertal spurts but the boys had not done so.

Judging from the fiftieth centile levels, the maximum rates of elongation occurred at about the same age for each of the three lengths in the girls. In boys, however, they occurred about one year later in S-N than in Ba-N or Ba-S. Consequently, the sex difference in timing for S-N (3.2 years) is considerably greater than those for Ba-N (2.5 years) and Ba-S (1.9 years).

The median rates of elongation that have been described indicate the levels, together with the accelerations and decelerations, noted in the "average" boy and girl. It is equally important to consider the distribution of these rates and the tenth and ninetieth centiles have been used for this purpose.

Figures 2-4 contain the tenth, fiftieth (median) and ninetieth centiles for the annual increments (mm/year) within chronological age intervals. It should be recalled that the tenth centile level would be exceeded by ninety among each one hundred children from the same group; similarly, the ninetieth centile level would be exceeded by only ten among each one hundred children from the same group. These graphs also indicate the range from the tenth to the ninetieth centile; eighty per cent of children from the same group would be within this range. In interpreting them it is important to note that membership in the groups of children either below the tenth centile or above the ninetieth centile is not fixed. For example, children whose elongation rates are below the tenth centile at eight to nine years may, or may not, have elongation rates below the tenth centile at nine to ten years.

The data for Ba-N (Fig. 2) show the median rates of elongation that were included in Figure 1. The ninetieth centile levels for rates of elongation, in each sex, were about 2-3 mm/year until 11.5 years. After this, the ninetieth centile levels decelerated rapidly in the girls to about 1 mm/year at 16.5 years. The sex differences at

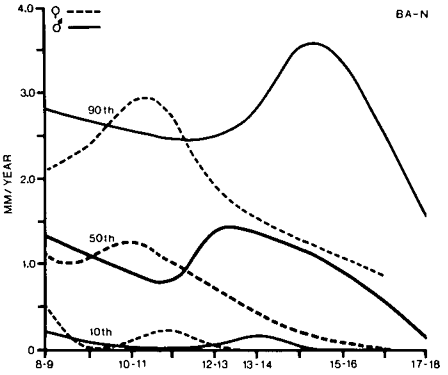

Fig. 2 Tenth, fiftieth (median) and ninetieth centiles for annual increments in Ba-N within chronological age intervals (mm/year).

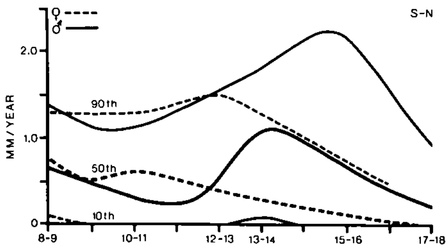

Fig. 3 Centiles for annual increments in S-N within chronological age intervals (mm/year).

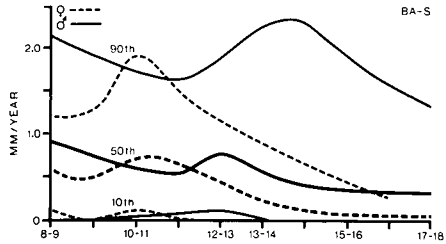

Fig. 4 Centiles for annual increments in Ba-S within chronological age intervals (mm/year).

later ages are striking: between 13.5 and 16.5 years the ninetieth centile rates were more than 3 mm/year for boys but were less than 1.5 mm/year in girls. During this latter part of the age range studied, the ninetieth centile levels were decelerating rapidly in each sex.

The tenth centile levels were low for all age intervals in each sex (zero-0.5 mm/year). The range from the tenth to the ninetieth centile was considerably smaller in girls than for boys, at all ages, except from 10 to 11.8 years. The order of ages at which the maximum elongation rates occurred, at the various centile levels, was fiftieth, tenth and ninetieth for boys but fiftieth, ninetieth and tenth in the girls.

The corresponding data for S-N (Fig. 3) show that, at the tenth centile level, most of the rates were close to zero in each sex. Expressed differently, there were at least ten per cent of children whose annual increments were close to zero during any one year. It is emphasized that the group of children in whom the rate of elongation was at or below the tenth centile may not contain the same children throughout the age range studied. At the other extreme of the distribution of elongation rates, the ninetieth centile levels were similar in each sex until 12.5 years, after which acceleration continued in boys but the rates decelerated rapidly in girls. At no age did the ninetieth centile level for the girls exceed 1.5 mm/year but in boys it was greater than this from 12.5 to 16.5 years. In each sex there was a marked trend for the maximum elongation rates to occur at increasingly later ages from the tenth to the fiftieth to the ninetieth centile levels. The range from the tenth to the ninetieth centile was similar in each sex until 12.5 years; after this age it became much greater in the boys than the girls.

In the corresponding data for Ba-S (Fig. 4), the tenth centile levels were near zero for all age intervals in both sexes. The ninetieth centile levels were higher for the boys than girls throughout the age range studied, except from

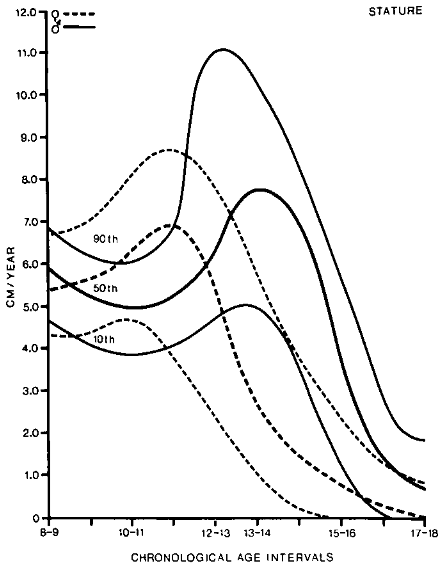

Fig. 5 Centiles for annual increments in stature within chronological age intervals (cm/year). The samples are the same as those used for the study of cranial base elongation.

about 10.2 to 11.2 years when the maximum rates of elongation occurred in the girls. At the ninetieth centile level the rate exceeded 1.5 mm/year in the girls between 9.8 and 11.5 years only. By contrast, the ninetieth centile rate for the boys was greater than 1.5 mm/year, for all age intervals, except the last (17-18 years). The fiftieth percentile levels (medians) were near zero after 14.5 years in the girls. In boys the rate of deceleration was very slight after 14.5 years and the median rate was still 0.3 mm/year at 17-18 years. The ninetieth centile levels, although showing evidence of rapid deceleration, did not become zero in either sex during the age range of the present investigation. The range of elongation rates (tenth to ninetieth centiles) was much greater for boys than girls at all ages except from about 9.5 to 11.5 years when the most rapid increases in the growth rate occurred in the girls. There was a relative lack of variation in elongation rates in girls after fifteen years.

Corresponding data for stature in the same children are presented in Figure 5. The median elongation rates were higher in the girls than in boys until about 12.5 years; later, the pubertal spurts became well-established in boys at ages when the median rate was decreasing for girls. In girls the median rate decreased to zero at 17-18 years but was still 0.7 cm/year for this interval in the boys. The maximum rate of elongation at the fiftieth centile level occurred at about 11.5 years in the girls but not until 13.5 years in the boys. The range from the tenth to the ninetieth centile was greater in the girls than the boys until about 12 years. The relative increases in median increments in stature at puberty were 56.6 per cent in boys and 27.8 per cent for girls; the difference in timing at the fiftieth centile level was about 2.2 years.

Figures 6-8 show selected centiles (tenth, fiftieth, ninetieth) for the rates of elongation of the three cranial base lengths within age intervals related to the age at onset of ossification in the ulnar sesamoid (US). The major effect of substituting a maturational age for chronological age was the elimination of almost all sex differences in the timing of pubertal accelerations.

The data for Ba-N (Fig. 6) demonstrate median rates of elongation that

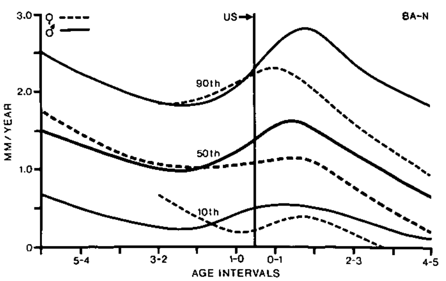

Fig. 6 Centiles of increments in Ba-N (mm/year) for annual intervals in relation to the onset of ossification in the ulnar sesamoid (US).

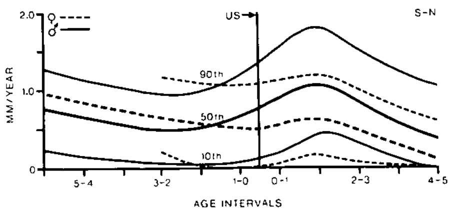

Fig. 7 Centiles of increments in S-N (mm/year) for annual intervals in relation to the onset of ossification in the ulnar sesamoid (US).

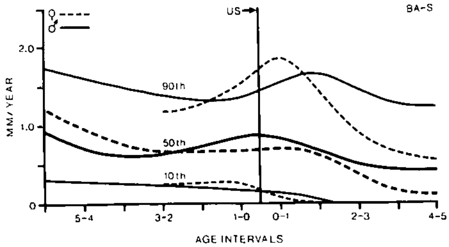

Fig. 8 Centiles of increments in Ba-S (mm/year) for annual intervals in relation to the onset of ossification in the ulnar sesamoid (US).

decelerated similarly in both groups until one or two years before US when a moderate acceleration occurred in boys. The acceleration in girls at the fiftieth centile level was small. The maximum rate of elongation occurred about 0.5 to 1.0 years after US in each sex and at each centile level. In boys there was a progressive increase in the apparent growth rate from the tenth to the fiftieth to the ninetieth centile. There was no regular progression in the girls in whom, somewhat surprisingly, the increase in velocity was much more obvious at the tenth centile level than at the fiftieth centile level.

The centiles for rates of elongation of S-N, when calculated for intervals related to US (Fig. 7), show that spurts occurred about 1.5 years after US in each sex for each centile level. For corresponding centiles, the increases in growth rates were more noticeable in the boys than the girls, to such an extent that, at about the time of the increases, the elongation rates at the ninetieth centile level for girls were only slightly greater than those at the fiftieth centile level for the boys, and the median rates for the girls were only slightly greater than the tenth centile rates for boys. By the interval four to five years from US, the elongation rates of S-N had become zero in each sex at the tenth centile level but, at the ninetieth centile level, the rates were about 1.1 mm/year for boys and 0.6 mm/year for girls.

The corresponding data for Ba-S show differences in the timing of spurts between the sexes, although the increments were calculated relative to US (Fig. 8). The spurts tended to occur earlier in girls than boys at the ninetieth centile level but not at the fiftieth. In boys spurts were not apparent at the tenth centile level; they were small at the fiftieth centile level and large at the ninetieth centile level. In the girls spurts were clearly present at the ninetieth centile level only. The most obvious difference between the sexes in the elongation rates of Ba-S was the more rapid deceleration in the girls after the pubertal spurts at the fiftieth and ninetieth centile levels. In each sex elongation was still occurring, even four to five years after US at the fiftieth and ninetieth centile levels. At corresponding centile levels these rates were about twice as great for boys as in the girls during the latter part of the age range studied.

Pubertal Spurts

Although the criteria for the recognition of pubertal spurts were set higher in boys than in girls, these spurts were observed with similar frequency in each sex (Table II). In both sexes spurts were most common in Ba-N and least common in Ba-S. The mean differences between the annual increments

TABLE II

The Incidence and Size (mm) of First Pubertal Spurts

Length	*Percentage Incidence*		*Mean Increments*					
			Before		*During*		*After*	
	Boys	*Girls*	*Boys*	*Girls*	*Boys*	*Girls*	*Boys*	*Girls*
Ba-N	93.1	95.1	0.5	0.6	2.5	2.0	1.5	0.8
S-N	86.2	85.3	0.2	0.2	1.5	1.2	0.9	0.4
Ba-S	79.3	68.3	0.3	0.3	1.8	1.4	0.6	0.4

TABLE III

Mean Ages of Occurrence of First Pubertal Spurts (Years)

Length	*Chronological Age*		*Interval Before PHV*		*Interval After US*		*Interval Before Menarche*
	Boys	*Girls*	*Boys*	*Girls*	*Boys*	*Girls*	*Girls*
Ba-N	12.8	11.4	0.8	0.3	0.3	0.9	1.5
S-N	13.3	11.5	0.3	0.3	0.7	1.0	1.4
Ba-S	13.0	11.3	0.5	0.5	0.4	0.8	1.6

PHV = Age of peak height velocity

US = Onset of ossification in ulnar sesamoid

immediately preceding the spurts and those during the spurts were greater in boys than girls. In each sex these differences were largest for Ba-N and smallest for Ba-S.

First pubertal spurts tended to occur about 1.4 to 1.8 years earlier in girls than in boys. This differed somewhat between the three cranial base lengths (Table III). These spurts occurred about 0.3 to 0.8 years before PHV (means) and about 0.3 to 1.0 years after US. There was little sex difference in their timing in relation to PHV but they occurred slightly earlier in boys than girls in relation to US. The mean ages of first pubertal spurts were about 1.5 years after menarche for each of the three lengths.

Discussion

Rates

This analysis has demonstrated marked sex-associated differences in the rates of cranial base elongation. For each of the three lengths a deceleration was followed by an acceleration; later there was a second deceleration. The accelerations occurred at about the age of puberty and about two to three years later in boys than girls. There were corresponding differences in timing between the sexes in the decelerations that succeeded these accelerations. Due to these differences, the median rates of elongation were not consistently greater in any sex across all ages, but the median rates were markedly greater in the boys than the girls for all three lengths after about twelve to thirteen years.

Pubertal spurts in Ba-N, S-N and Ba-S have been reported previously in these same children from the Fels sample. Others[4-8] have reported pubertal accelerations in the rates of elongation of S-N but the age ranges of earlier studies, the sizes of the samples included, and the manner in which the data have been presented make it difficult, if not impossible, to compare earlier findings with those reported previously from the present sample. The most comprehensive set of data from other children has been reported by Sekiguchi et al. for S-N.[9] The patterns of change across age in their data are similar to those found in the present study but their means exceed the present medians at all ages.

To facilitate comparisons between

boys and girls for each cranial base length and for stature, the variability of elongation rates (mm/year or cm/year) was calculated as the difference between the ninetieth and the tenth centile levels divided by the fiftieth centile level. This was calculated for the age intervals ten to eleven years (near the age of pubertal spurts in the girls), twelve to thirteen years and fourteen to fifteen years. The latter interval is close to the age of pubertal spurts of boys. When calculated in this fashion, the sex differences in variability were small from ten to eleven years. From twelve to thirteen, the rates were more variable in girls than boys for each cranial base length, but not for stature. From fourteen to fifteen years, with the exception of Ba-S, the rates of elongation were more variable in girls than boys for both the cranial base lengths and stature. To a large extent these sex differences were due to changes in the median rates which were used as the denominator. During the later age interval these median rates were much slower in the girls than the boys.

If variability were considered the range from the tenth to the ninetieth centile, the conclusions regarding sex-associated differences in variability would change. On the latter basis the sex differences would be small for the first two age intervals but, from fourteen to fifteen years, variability would be considerably greater in boys than in girls.

Age of Maximum Increments

The mean ages at which the maximum rates of growth occurred for each cranial base length ranged from 12.6 to 13.7 years in boys but were close to 10.5 years in the girls (Fig. 1). In the same children the corresponding ages for stature were 13.6 years for boys and 11.7 years in girls (Fig. 5). These ages for S-N agree, in general, with those reported by Sekiguchi et al.;[9] those for stature correspond closely with those reported by others.[10-12]

Substitution of a biological age for chronological age removes many of the sex differences in the timing of pubertal accelerations. The biological age used for this purpose was age in relation to the onset of ossification of the ulnar sesamoid. Another measure of biological age, for example skeletal age, age in relation to menarche, or age in relation to peak height velocity could have been used. It is reasonable to assume that the choice of biological age would have influenced the results only slightly.

When the median rates of elongation, in relation to ulnar sesamoid ossification for boys and girls, were compared, the major difference was not in the timing of the maximum increments but in the actual rates (mm/year) at those times. For each cranial base length, not only were the median rates considerably greater in the boys than the girls throughout the pubertal accelerations and later decelerations, but the pubertal accelerations themselves were much greater in boys.

Sequence of Maximum Increments

Little attention has been given to the timing of maximum increments in length either in the cranial base or the long bones; furthermore, the sequence of maximum increments has been neglected almost entirely. Comprehensive data have been reported by Stolz and Stolz[13] but these data were obtained by standard anthropometric techniques and, therefore, are less reliable than corresponding data from standardized radiographs.[14,15]

Recently,[16] an analysis has been made of radiographic data and of stature for children in the Fels sample. This analysis demonstrated that the order of mean ages at which maximum rates of elongation occur in particular bones and cranial base lengths is similar in both sexes. All the variances of these ages are high. Furthermore, the sequence of maximum increments among bones, cranial base lengths and stature differ within individuals. For example, the maximum increment in S-N may occur *before* all the following or *after* all the following: menarche, onset of ossification in the ulnar sesamoid, and maximum increments in biiliac diameter (pelvis), radius, tibia, stature, metacarpal II, Ba-N and Ba-S.

The cause of this variability in sequence is unknown. It is reasonable to assume that the same hormones are responsible for the increased rates of elongation in the cranial base and the long bones and for the acceleration in stature. Consequently, it must be assumed that these variations in sequence reflect differences within individuals in the sensitivity of end organs (chondrocytes in growth zones) to levels of circulating hormones.

Pubertal Spurts.

Spurts in S-N for boys and girls have been reported previously[4,5,6,8] but the earlier samples were small and the findings somewhat inconclusive. The most convincing earlier study was by Brown and his co-workers[7] who found spurts in S-N in Australian aboriginal children. In the Fels children, pubertal spurts in cranial base lengths were almost equally common in each sex in the three cranial base lengths. Although different criteria were used to define a spurt in the two sexes, these criteria had similar relationships to the sex-specific prepubertal rates of elongation. In each sex, spurts in Ba-N were more common than in the other lengths and the accelerations associated with the spurts tended to be greater for Ba-N than for the other lengths.

For each cranial base length the mean acceleration associated with pubertal spurts was greater in the boys than the girls. The mean rates of elongation of S-N during the spurts were less in the present children than in those studied by Brown et al.[7] These differences may be, in part, ethnic in origin or may reflect the fact that Brown and his co-workers selected children for study who had well-marked pubertal spurts in stature.

In our sample, pubertal spurts in cranial base lengths tended to occur about 1.4 to 1.8 years later in boys than girls. The differences in timing were much smaller when considered in relation to ulnar sesamoid ossification or age at peak height velocity. The timing of spurts in each sex was related closely to skeletal age; this is in agreement with earlier findings for S-N.[8,17,18] A similar close relation between the timing of spurts in the cranial base and biological age has been reported by Brown et al., who found this association was closer with age of peak height velocity than with skeletal age. These findings provide evidence that the spurts in the recorded data were real. Admittedly, they were small but the error of measurement was small also.

Earlier workers have reported that pubertal spurts in S-N tend to occur after PHV;[4,5] in the present children first spurts tended to precede PHV. In Fels girls the mean increments during pubertal spurts were larger in tall than in short girls. In addition, they were larger in those girls with only a short interval between PHV and menarche as opposed to those with a long interval. It was considered that the former girls passed quickly through puberty.

The median rates of elongation before pubertal accelerations were compared with the maximum rates during puberty. The increases associated with puberty were expressed as percentages of these earlier rates. The relative increases were markedly greater in boys than in girls for Ba-N and S-N but were similar in each sex for Ba-S. These findings for Ba-N are in general agreement with those of Sekiguchi et al.[9] They are in agreement with age trends for sex differences between means for S-N reported by Nanda[4] and Pedersen.[6] In the present study the relative mean increases in stature increments at puberty were greater in the boys than the girls but, for each sex, the relative increases were less than those in one or more of the cranial base lengths. These findings show that, although the cranial base elongates slowly, the relative increase in its rate of elongation at puberty is similar to, or greater than, that in stature.

The cranial base elongates until maturity in primates[19,20] and pubertal spurts occur in apes.[19] In addition, the patterns of resorption and apposition on the cranial base in man occur in monkeys also.[21,22]

The increases in cranial base lengths during the circumpubertal period have been compared with the corresponding increases in stature in the same children. To facilitate this comparison, the same age range (10 to 18 years) was used in each sex and the increase in each length and in stature was expressed as a percentage of its sex-appropriate mean length at eighteen years in the same children. These percentages were markedly greater in boys than in girls for each cranial base length and moderately greater for stature (Table IV). Sekiguchi et al., reported slightly greater mean absolute increases in Ba-N in boys than in girls from nine to fifteen years; all of this sex difference occurred after thirteen years.

These findings can be compared with those of Coben,[23] who reported that, from eight to sixteen years, the absolute increments in Ba-N were larger in boys than in girls but there was only a small corresponding sex difference in Ba-S. In addition, Nanda[24] reported larger increases in S-N from ten to seventeen years in boys than girls, when these increases were expressed as percentages of the lengths at seventeen years.

TABLE IV

Median Increments from Ten to Eighteen Years Expressed as Percentages of the Eighteen-Year Values

	Boys	*Girls*
Ba-N	8.8	4.7
S-N	8.1	3.2
Ba-S	12.2	7.6
Stature	21.4	14.9

The Cessation of Elongation

The present median values show that elongation was continuing at 17.5 years for each length in the boys. In the girls the median rates were zero at 16.5 years for Ba-S and at 17.5 years for Ba-N and S-N. In the children studied by Pedersen,[6] Ba-S ceased to elongate at about fifteen years in one boy and at thirteen and eighteen years in two girls. The data for the other children he studied did not extend into the appropriate age range. The ages of cessation for Ba-S in this study are later than those reported by Melsen[25] for the cessation of elongation in the clivus.

After smoothing, the data of Nanda[24] indicate ages of cessation of elongation in S-N ranging from seventeen to twenty years in eight boys and from thirteen to fifteen years in five girls. In addition, Hunter[26] reported that S-N had reached ninety-seven to ninety-eight per cent of its final size at the end of the year of maximum facial growth. In Hunter's sample the end of the year of maximum facial growth occurred during wide chronological age ranges (11.75 to 15.75 years in boys; 8.75 to 13.75 years in girls). Hunter determined final size from the last available radiograph; the age ranges of these were 16.75 to 26.1 years in the boys and 13.75 to 25.0 years in the girls.

The present data are consistent with earlier reports that elongation tends to cease earlier in girls than boys. They extend earlier findings concerning S-N to include Ba-N and Ba-S. It must be stressed, however, that the present data are inadequate to allow a definitive conclusion concerning the age of cessation of elongation. However, many of these children have later serial radiographs and it is intended that the study will be extended with this question in mind.

The cessation of elongation in cranial base lengths can be considered in relation to ulnar sesamoid ossification. During the interval from four to five years after ulnar sesamoid ossification, which is the last for which data are currently available, elongation was still occurring in each sex with median values of 0.4 to 0.7 mm/year in the boys and 0.1 to 0.2 mm/year in the girls for the three cranial base lengths.

When these later data are analyzed, the statistical approach may be similar to that used recently in another study. The age of cessation of growth in stature has been analyzed using data from 103 boys and 91 girls in the Fels sample.[27] Using serial data for each child, a two-degree polynomial was fitted to the earlier data and a horizontal straight line (0-degree polynomial) was fitted to the later data. These two lines were fitted using all possible junctions between earlier and later sets of data. The age of the junction at which the goodness of fit was maximized for the two lines combined was considered the age at which growth in stature had ceased. According to this mathematical approach, the mean ages of cessation in stature were 21.2 years in the boys and 17.3 years in the girls, with considerable variability of ages in each sex. These mean ages are in close agreement with those reported following analyses of less complete serial data from smaller samples.[28,29]

All estimates of ages when elongation ceases, whether in the cranial base or stature, cannot be more than approximations. As the increments decrease to approximate zero, the errors of measurement become relatively more important. Furthermore, serial examinations, if scheduled at all, are more widely spaced in late adolescence.

Possible Sites of Elongation

The total increments in cranial base lengths from 9.5 to 18 years were not small. Considering median values, they ranged from 3.0 mm (S-N in girls) to 9.8 mm (Ba-N in boys). Five mechanisms could be responsible, singly or in combination, for elongation of the cranial base during and after puberty. These are:

(a) *apposition at basion.* This occurs before and after fusion at the spheno-occipital synchondrosis,[39] but the amount is small. It must be accompanied by resorption at and near opisthion and repositioning of the foramen magnum because the anteroposterior diameter of the foramen remains almost unchanged after childhood.[31,34] This pattern of remodeling has been described in man[21] and in monkeys.[22] It would tend to increase the distances Ba-N and Ba-S. It is associated with an increase in the distance from the tuberculum sellae to basion.[35]

(b) *repositioning of sella.* In this study the S point was defined as the midpoint of the pituitary fossa, by inspection, on the radiograph. The pituitary fossa enlarges during and after puberty.[36-40] This enlargement is accompanied by resorption on the posterior wall and apposition on the anterior wall of the fossa.[36-38,41] This repositioning is presumably small in amount because the total increment, from eight to sixteen years, in the distance from S to the endocranial aspect of the frontal bone does not exceed two mm.[42] This posterior repositioning would tend to elongate S-N and shorten Ba-S.

On the floor of the pituitary fossa, the pattern of remodeling may be one of resorption or apposition.[8,21,43,44] These changes would shift S in or near a vertical plane. They are known to occur from histological and cephalometric studies in man, and implant studies show that they occur in monkeys.[22] This "vertical" repositioning would have little effect on the lengths being considered.

(c) *repositioning of nasion.* The usual pattern of remodeling at nasion is apposition[21,31,34,40,45] which would tend to increase the distances Ba-N and S-N. From eight to sixteen years the mean increase in the thickness of the frontal bone, including the sinus, at N is 5.2 mm in boys and 3.1 mm in girls.[46] Most of this sex difference is due to growth after twelve years.[47] When serial tracings are registered on the outline of the anterior part of the cranial base, N may move superiorly or inferiorly.[31,43,44,48,49] These changes are relatively small and, presumably, would have little influence on the apparent rates of elongation of Ba-N and S-N.

(d) *change in the saddle angle.* Strictly, this is not a site of elongation. A decrease in the saddle angle (either Ba-S-N or an approximately equivalent angle) would not affect the S-N and Ba-S lengths directly but would tend to reduce the Ba-N distance. Although remodeling on the endocranial aspect of the cranial base is generally resorptive, this is more marked on the posterior part of the clivus than elsewhere.[50] Consequently, the clivus becomes more vertical during growth.[34,51,52] Nevertheless, the changes in the saddle angle after puberty are reported to be slight;[6,34,35,40,51,53,54] this is in agreement with findings from the present children (Lewis and Roche, unpublished).

(e) *apposition at the spheno-occipital synchondrosis.* During childhood this synchondrosis is an important site of cranial base elongation, although, in experimental animals,[55,56] its growth potential after transplantation is not as marked as that of an epiphyseal zone. Bony fusion at this site occurs at about fifteen to sixteen and a half years in boys and eleven to fourteen years in girls.[25,30,36,47] The age of its fusion is associated closely with skeletal age.[57] Elongation of Ba-S after these chronological age ranges for fusion at the synchondrosis has been reported;[58,59] corresponding changes occurred in the present children. Nevertheless, there are contrary reports that Ba-S did not increase from fifteen to twenty-two years in cross-sectional material[34] and that it ceased to elongate at a mean age of 16.1 years in girls studied serially.[17]

Possible Brain Stem Changes

The finding that cranial base elongation continues until at least 17.5 years in boys and 16.5 years in girls indicates that there may be corresponding elongation of the brain stem. The brain stem consists of the midbrain, pons and medulla oblongata and its possible elongation refers to lengthening in the plane of the posterior part of the cranial base. It is considered that the division of neurones ceases during the first year after birth, although an increase in glial cells may occur later.[60-62] There is tentative evidence that the brain stem becomes smaller with age during adult life,[63] but data have not been reported concerning its changes in length during puberty and adolescence. Necessarily, any such data must be cross-sectional and based on postmortem observations.

From the earlier discussion it is clear that there is a pubertal spurt in S-N and elongation of S-N after puberty. There is apposition on the ectocranial surface at N but there is no deposition at the inferior surface of the frontal bone on its endocranial aspect.[21] There is posterior movement of S. Consequently, it is reasonable to assume that an increase occurs in the distance from the pituitary gland to the frontal pole of the cerebral cortex.

Correspondingly, pubertal spurts and postpubertal elongation occur in Ba-S. These occur despite any posterior migration of S. They must be associated with posterior migration of the foramen magnum for which there is confirmatory evidence.[21] These changes imply an increase in the distance from the pituitary fossa to the inferior border of the medulla oblongata.

Another remote possibility is that the dura mater increases in thickness at puberty and comes to occupy the additional space made available by cranial base elongation. There are few relevant data and those available have been obtained in postmortem studies of adults. These show only a slight increase with age in the volume of the dura mater after 30 years.[64,65]

The question could be posed in the form: Does the foot fit the shoe? There is no doubt the shoe (cranial base) elongates during and after puberty. Any associated changes in the thickness of the sock (dura mater) must be small. It is reasonable to postulate an elongation of the foot (brain stem) so that it continues to fit the enlarging shoe.

Summary

Findings concerning the circumpubertal elongation of the cranial base have been reviewed with special reference to sex differences. In boys and girls, for the three cranial base lengths considered, decelerations were followed by accelerations at about the age of puberty; decelerations occurred later. Within each sex the relative increases in the median rates of elongation of cranial base lengths at puberty exceeded those for stature, except for S-N in the boys and Ba-S in the girls. The relative increases in the rates of elongation at puberty were markedly greater in boys than girls for Ba-N and S-N but not for Ba-S. The median total elongation from 9.5 to 17.5 years, for each length, was greater in the boys than the girls. This reflects sex differences in gains during puberty and in rates of elongation before and after puberty.

Pubertal spurts in stature occurred about two years later for boys than girls. There was a similar sex difference in the timing of pubertal spurts in cranial base lengths. These sex differences in timing were reduced markedly when a biological age, based on the onset of ossification in the ulnar sesamoid, was substituted for chronological age. Pubertal spurts were common in each sex with the highest incidence in Ba-N and the lowest in Ba-S. These spurts were larger in the boys than the girls.

These findings have been discussed with relation to elongation mechanisms in the cranial base and their implications with reference to elongation of the brain stem.

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