The pattern of facial skeletal growth and its relationship to various common indexes of maturation

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Introduction: Sequential stages in the development of the hand, wrist, and cervical vertebrae commonly are used to assess maturation and predict the timing of the adolescent growth spurt. This approach is predicated on the idea that forecasts based on skeletal age must, of necessity, be superior to those based on chronologic age. This study was undertaken to test this reasonable, albeit largely unproved, assumption in a large, longitudinal sample. **Methods:** Serial records of 100 children (50 girls, 50 boys) were chosen from the files of the Bolton-Brush Growth Study Center in Cleveland, Ohio. The 100 series were 6 to 11 years in length, a span that was designed to encompass the onset and the peak of the adolescent facial growth spurt in each subject. Five linear cephalometric measurements (S-Na, Na-Me, PNS-A, S-Go, Go-Pog) were summed to characterize general facial size; a sixth (Co-Gn) was used to assess mandibular length. In all, 864 cephalograms were traced and analyzed. For most years, chronologic age, height, and hand-wrist films were available, thereby permitting various alternative methods of maturational assessment and prediction to be tested. The hand-wrist and the cervical vertebrae films for each time point were staged. Yearly increments of growth for stature, face, and mandible were calculated and plotted against chronologic age. For each subject, the actual age at onset and peak for stature and facial and mandibular size served as the gold standards against which key ages inferred from other methods could be compared. **Results:** On average, the onset of the pubertal growth spurts in height, facial size, and mandibular length occurred in girls at 9.3, 9.8, and 9.5 years, respectively. The difference in timing between height and facial size growth spurts was statistically significant. In boys, the onset for height, facial size, and mandibular length occurred more or less simultaneously at 11.9, 12.0, and 11.9 years, respectively. In girls, the peak of the growth spurt in height, facial size, and mandibular length occurred at 10.9, 11.5, and 11.5 years. Height peaked significantly earlier than both facial size and mandibular length. In boys, the peak in height occurred slightly (but statistically significantly) earlier than did the peaks in the face and mandible: 14.0, 14.4, and 14.3 years. Based on rankings, the hand-wrist stages provided the best indication (lowest root mean squared error) that maturation had advanced to the peak velocity stage. Chronologic age, however, was nearly as good, whereas the vertebral stages were consistently the worst. Errors from the use of statural onset to predict the peak of the pubertal growth spurt in height, facial size, and mandibular length were uniformly lower than for predictions based on the cervical vertebrae. Chronologic age, especially in boys, was a close second. **Conclusions:** The common assumption that onset and peak occur at ages 12 and 14 years in boys and 10 and 12 years in girls seems correct for boys, but it is 6 months to 1 year late for girls. As an index of maturation, hand-wrist skeletal ages appear to offer the best indication that peak growth velocity has been reached. Of the methods tested here for the prediction of the timing of peak velocity, statural onset had the lowest errors. Although mean chronologic ages were nearly as good, stature can be measured repeatedly and thus might lead to improved prediction of the timing of the adolescent growth spurt. (Am J Orthod Dentofacial Orthop 2013;143:845-54)

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The authors report no commercial, proprietary, or financial interest in the products or companies described in this article.
Based on a manuscript awarded the 2007 Graber Clinical Award of the American Association of Orthodontists.
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Submitted, June 2009; revised and accepted, January 2013.
0889-5406/$36.00

http://dx.doi.org/10.1016/j.ajodo.2013.01.019

Milo Hellman's observation[1,2] that facial growth undergoes periods of acceleration and deceleration was a major advance in the understanding of facial growth. Today, it is generally accepted that treatment during the so-called adolescent growth spurt increases the efficiency and effectiveness of orthodontic treatment, especially for a Class II malocclusion.[3-5] For stature, the peak of the adolescent spurt is generally thought to occur at approximately ages 12 years in girls and 14 years in boys. The onset of the spurt occurs approximately 2 years before the peak.[6-11] Although mean chronologic age can serve as a guide to treatment timing, there are sufficient individual variations to prompt investigators to search for some sort of skeletal age that might be better correlated with the growth of the face.[11-16]

Because of the recognizable sequence of developmental stages and the ease with which radiographs can be obtained, hand-wrist staging is perhaps the most common method of assessing skeletal maturation. Many investigators, however, have found that several key hand-wrist events (eg, the appearance of the adductor sesamoid) appear at or near the peak of the pubertal growth spurt and thus have little use in prediction of the spurt's onset.[8,9,17-21] The observation that other areas of the skeleton progress through a series of well-defined changes during puberty has led orthodontists to look to these events to assess maturation and predict the timing of facial growth.

The cervical vertebrae undergo a well-defined sequence of changes that are visible on routine lateral cephalometric radiographs.[22,23] These events are correlated with the stages of the hand and wrist and thus might serve to assess a patient's current developmental status.[24-29] The original method of staging by Lamparski,[22] however, does not seem to lend itself to a statistically efficient prediction of future growth.[30] Recently, however, several groups have developed new vertebral scales that warrant consideration, both as methods of assessing present maturity and for predicting the timing of future growth.

Franchi et al[31] and Baccetti et al[32,33] modified the methods of Lamparski[22] and produced a single set of standards for both sexes. With respect to these new standards, they found that the peak in mandibular growth occurs between cervical vertebral stages (CS) 3 and 4 and that the stages of vertebral maturation occur, on average, 1 year apart. Thus, CS 2 might be a basis for prediction in that it would tend to precede the interval of maximum mandibular growth by about a year.

As things stand, indexes of skeletal maturation are the generally accepted means of assessing "growth potential"; however, the various methods are based on relatively small samples and commonly are validated against statural growth rather than a more obvious gold standard: the growth of the various regions of the face. The purpose of this investigation, therefore, was to develop incremental growth curves for stature, facial size, and mandibular length for a large longitudinal sample of growing children. As determined from these curves, the timing of major growth events (onset and peak) will be compared, with both the mean ages at which these events are supposed to occur and the estimated ages at which key hand-wrist and cervical vertebral stages appeared. Our goal was to test the common supposition that estimates of maturation and prediction based on bone age have smaller errors than estimates based on chronologic age or stature.

MATERIAL AND METHODS

We used the serial records of 100 subjects (50 girls, 50 boys) from the files of the Bolton-Brush Growth Study Center in Cleveland, Ohio. The participants in the Bolton study were certified by their family physician as "well and normal." Because the main goal of this study was to examine the individual pattern of growth, practically the only criterion for inclusion was the availability of a long (>6 years), unbroken series of lateral cephalograms, hand-wrist radiographs, and statural records. Class III subjects were excluded. In all but a few instances, the radiographs were taken at yearly intervals (± 30 days). A few subjects (3 girls, 18 boys) had undergone limited orthodontic treatment, mainly space maintenance and anterior alignment. It was assumed—albeit without proof—that this sort of intervention had little appreciable effect on the skeletal cephalometric measures used here.

Initially, each series was 6 years in length, an interval designed to surround vertebral stage 3 development.[32] Analysis of the first 60 subjects, however, showed that this time span frequently did not contain an obvious spurt in facial growth. In an attempt to capture this event (if present), data were added as needed to extend all series back to at least age 8 for girls and age 10 for boys. Furthermore, if the onset and the peak of the facial growth spurt could not yet be detected, the older end of the series was added. Ultimately, the number of data sets in the 100 series ranged from 6 to 11. In all, the timing of facial growth was inferred from 808 serial lateral cephalograms.

The cephalograms were hand traced on 0.003-in matte acetate by one of 2 authors (Z.J.M. and L.E.J.). To ensure consistency, the first author's tracings were checked by the third author. Each series was traced at a single sitting so that anatomic details (especially the mandibular condyle) could be coordinated from one film to the next. The tracings then were digitized (digitizing board model A30BL.H; Numonics, Montgomeryville, Pa) and analyzed with commercial digitizing software (version 7.02; Dentofacial Planner, Toronto, Ontario, Canada). The Bolton cephalograms were taken at a minimum object-film distance. Thus, the average magnification ranged from 7.4% at age 8 to 8.4% at age 18.[34] It was assumed that this small variation would not alter the form of the resulting growth curves, and no correction was made.

Five measurements (Na-Me, S-Go, S-Na, PNS-A, Go-Pog) were summed to give an overall representation of facial size. A sixth measurement (Co-Gn) was used to analyze mandibular growth separately relative to the growth of the rest of the face (Fig 1).

With the aid of random numbers generated by variations in atmospheric pressure, 8 series (57 radiographs) were selected and reanalyzed.[35] Because there were 2 workers, each redid 2 of his own series and 2 of his colleague's, thereby permitting the use of intraclass correlation (ICC) to characterize technical reliability. For both interrater and intrarater reliabilities, the ICC values for the summed measurements of facial size and mandibular length exceeded 0.96.

On each cephalogram, the cervical vertebrae were staged according to the 6 stages of maturation described by Baccetti et al.[32] Their method is based on changes in shape of the cervical vertebral bodies (2-4) and developing concavities on their lower borders. Staging was effected by inspection, and a cephalometric analysis was partially adopted from Hellsing[36] and Baccetti et al.[33] San Román et al[26] reported that a concavity greater than 1 mm is the most reliable characteristic of maturation. For our study, a millimeter gauge was used to measure this characteristic on the lower border of cervical verbebra 3.

For most series, hand-wrist films were available at all ages. The films were staged according to Fishman's system[37] of skeletal maturation assessment by the principal investigator (Z.J.M.) and checked by a coauthor (R.G.B.).

Yearly increments of stature, facial size, and mandibular length were calculated for each subject and plotted against intervals of chronologic age (Microsoft Excel; Microsoft, Redmond, Wash). On the resulting growth curves, spline interpolation lines (version 14.0; SPSS, Chicago, Ill), the onset of the growth spurt was identified as the smallest increment—the local minimum—immediately preceding a relatively continuous increase to a peak—the local maximum. Some curves, however, deviated from the classic form first depicted by Scammon[38] in 1927. Occasionally, for example, 2 peaks were observed. If they were separated by a smaller increment, the average age of the 2 maxima was taken as the peak. To qualify for averaging, the multiple peaks had to be within 2 mm of each other on the facial growth curve, 0.5 mm on the mandibular growth curve, and 5 mm on the height curve. Despite individual variations, onset and peak ultimately were assigned with reference to points at which the curves had a slope of zero (ie, $dy/dx = 0$).

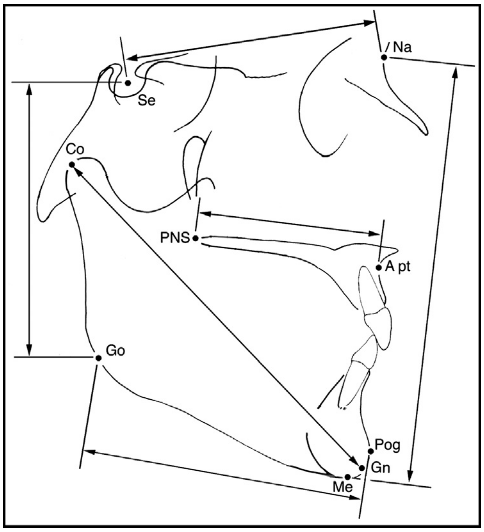

Fig 1. Cephalometric measures of facial size: Se-Na + Se-Go + Go-Pog + Na-Me served as a measure of facial size. Co-Gn served to measure mandibular size.

Chronologic age, hand-wrist stage, and vertebral stage at onset and peak then were estimated for each subject. Age was interpolated to the nearest quarter year. When onset or peak occurred at a half-year or a three-quarter-year point, the corresponding hand-wrist and vertebral stages were taken from the next time point's records. For 7 subjects, height data were unavailable for portions of the series, and thus neither statural onset nor peak could be identified.

For both the male and female subsamples, average growth curves were plotted for height, facial size, and mandibular length. To generate these curves, the individual peaks were aligned (registered), and the increments for the peak and each prior and succeeding interval were averaged. Intervals at the 2 tails with fewer than 10 subjects were not included in the averaged curves.

Each index studied here is commonly used to assess maturational progress relative to a modal stage at which peak growth is said to occur. For the Fishman hand-wrist method,[37] peak growth is said most often to occur in girls at stage 5 for height and stage 6 for the face; in boys, it tends to occur at stage 6 for height and stage 7 for the face. For the cervical vertebrae, the modal event is the midpoint between CS 3 and CS 4. As a baseline for comparison, assessments based on mean ages taken from the literature also were tested: onset, 10 years for girls and 12 years for boys; peak, 12 years for girls and 14 years for boys.[6,8-11,16]

In each of the 100 series, the age at which these key events occurred was estimated by interpolation and compared with the actual timing of the onset and the peak in stature, facial size, and mandibular length. Because the errors in the various estimates of maturation (estimated minus actual) would tend to sum to zero, the arithmetic mean would be meaningless. Instead, for each event and structure, the errors were squared, summed, and then averaged. The square root of each of these averages— the so-called root mean squared error—expresses error in years (rather than years squared) and thus is a sort of error standard deviation.

Indexes of maturation are also used to predict the timing of the adolescent acceleration. Three separate predictions of the peak age were generated from the vertebral method: age at CS 2 plus 1, 1.5, and 2.0 years. Stature was used to predict the peak by using the age at onset plus 2 years. In addition, predictions of onset and peak were generated based on mean chronologic age from other studies (girls, 10 and 12 years; boys, 12 and 14 years). The linear correlation between predicted and actual was calculated, and root mean squared errors (error standard deviations) were generated as estimates of the accuracy of each method. As with the assessment of maturation, facial and mandibular cephalometric data were taken to be the gold standards for the validation of the various methods of prediction.

Statistical analysis

Descriptive statistics were calculated with a commercial spreadsheet program (Microsoft Excel). Means, standard deviations, ranges, and confidence intervals were calculated for chronologic age at onset and peak for facial size, mandibular length, and height. Differences between means within the sexes were analyzed at both onset and peak by paired *t* tests (SPSS). For the hand-wrist and vertebral stages, modes were calculated to identify the stage that occurred most frequently at the peak of the statural, facial, and mandibular curves. The root mean squared errors for the various methods were ranked within sexes and structures, and the rankings were then tested with the Friedman blocked nonparametric analysis of variance.[39]

RESULTS

Descriptive statistics for the timing of the onset and the peak of the pubertal growth spurt are summarized in Table I. The average growth curves for stature, facial size, and mandibular length are depicted in Figures 2 through 7. Between sexes and among the 3 measures of size, the curves display a similar shape, with onset and peak clearly discernible on each curve. Girls seem to show a preadolescent spurt that closely precedes the pubertal growth spurt, whereas boys show a relatively constant growth rate up to the onset of the spurt. In boys, the average peak yearly increments in height and mandibular length were 95.35 and 4.79 mm, respectively. The average peak increments for girls were 82.70 mm for height and 3.88 mm for mandibular length.

Table I. Onset and peak: descriptive statistics

		Statistics (y)			
Structure	*Event*	*Mean*	*SD*	*Range*	*95% CI*
Boys					
Height	Onset	11.93	0.98	9.5-13.5	11.64-12.21
	Peak	13.99	1.03	12.5-17.5	13.7-14.29
Facial composite	Onset	11.95	1.08	10.25-15.5	11.64-12.26
	Peak	14.35	1.14	11.75-17.5	14.02-14.68
Mandibular length	Onset	11.86	1.27	10.25-15.75	11.49-12.23
	Peak	14.34	1.12	12-17.5	14.02-14.66
Girls					
Height	Onset	9.29	0.98	7.5-12.5	8.98-9.60
	Peak	10.92	0.99	9-13.75	10.63-11.20
Facial composite	Onset	9.77	1.19	7.5-13.5	9.43-10.11
	Peak	11.52	1.16	9.75-14.75	11.18-11.85
Mandibular length	Onset	9.54	1.12	7.5-13.5	9.21-9.86
	Peak	11.50	1.24	9.5-15	11.14-11.85

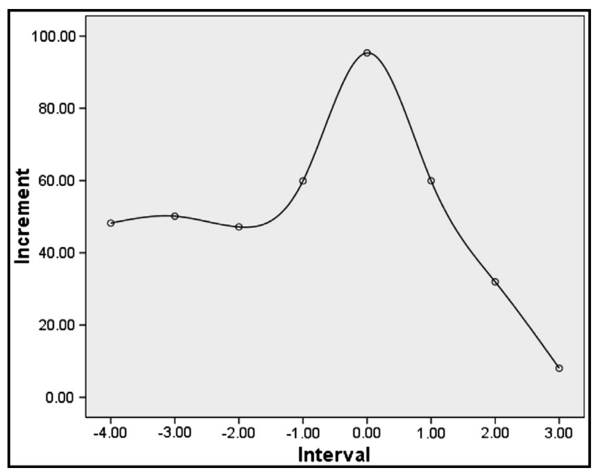

Fig 2. Average statural growth curve for boys. Individual curves registered on their peaks; 0.00 corresponds to a mean age of 13.99 years. Note that various figures have different x- and y-axis scales.

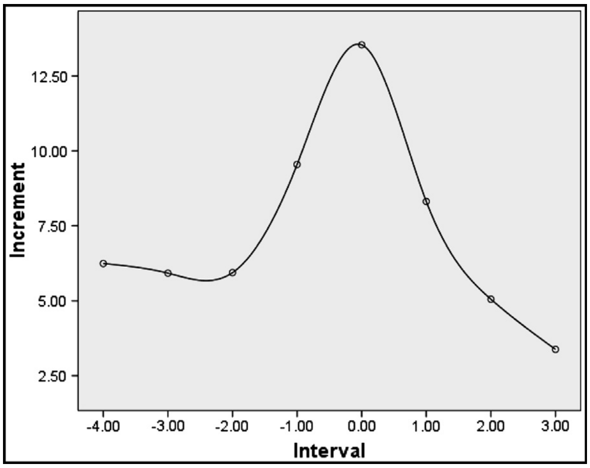

Fig 3. Average facial growth curve for boys; 0.00 corresponds to a mean age of 14.35 years.

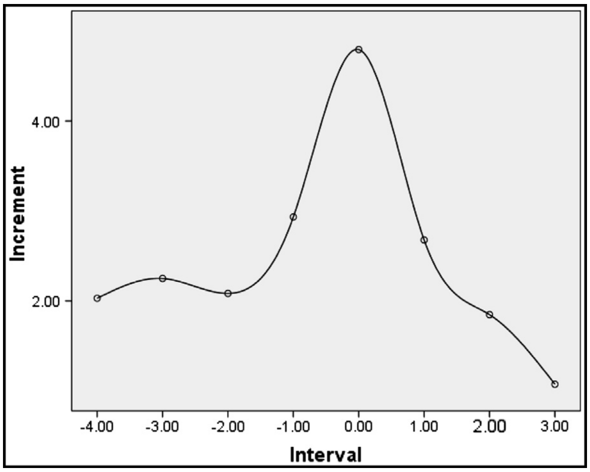

Fig 4. Average mandibular growth curve for boys; 0.00 corresponds to a mean age of 14.34 years.

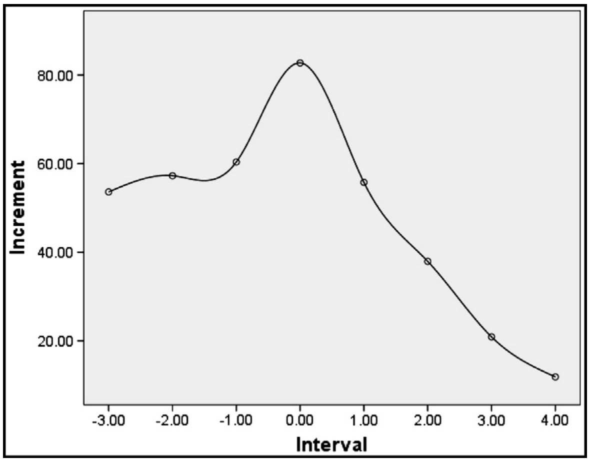

Fig 5. Average statural growth curve for girls; 0.00 corresponds to a mean age of 10.92 years.

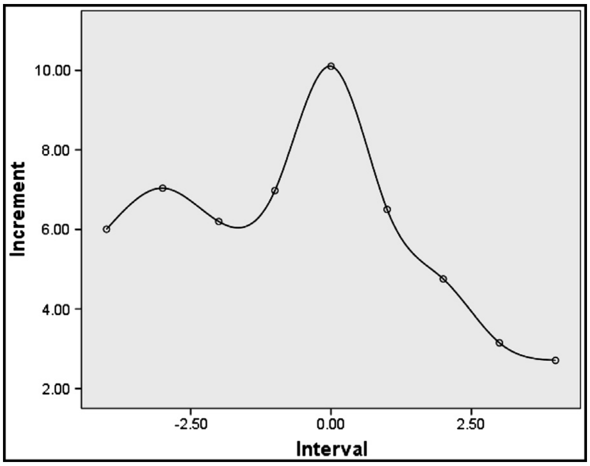

Fig 6. Average facial growth curve for girls; 0.00 corresponds to a mean age of 11.52 years.

The hand-wrist and cervical vertebral stages at onset and peak of the growth spurt are summarized in Table II. Although certain stages tend to be related to onset and peak, there is a wide range, and the modal percentages are quite low. Paired *t* tests show that, in boys, the peak occurred significantly earlier for stature than for facial size and mandibular length (Table III), whereas in girls, both onset and peak for height occurred significantly earlier than these events in the face and mandible.

As indexes of maturation, errors attendant to the use of averages from the literature (10 years for girls; 12 years for boys) to identify the probable occurrence of onset are given in Table IV. For peak growth, linear correlation (between assessed and actual) and errors (root mean squared error for assessed minus actual) for the average ages (12 years for girls; 14 years for boys), hand-wrist stages (Fishman stages 6 and 7 for boys, and 5 and 6 for girls), and the cervical vertebrae (CS 3.5) are summarized in Table V. Among the 3 methods of assessment, ages estimated from Fishman's hand-wrist method show the best correlation and smallest root mean squared error. Mean ages are the next best, and stage CS 3.5 is the worst. Based on the 1-2-3 rankings for the 3 dimensions in the sexes, the differences are significant ($\chi^2 = 10.3$; $P < 0.01$).

Table VI summarizes the correlations between actual peak ages and the peak ages predicted from the various indexes, along with the errors for each method. The predictions generated from height onset plus 2 years show the best correlation and the lowest errors for

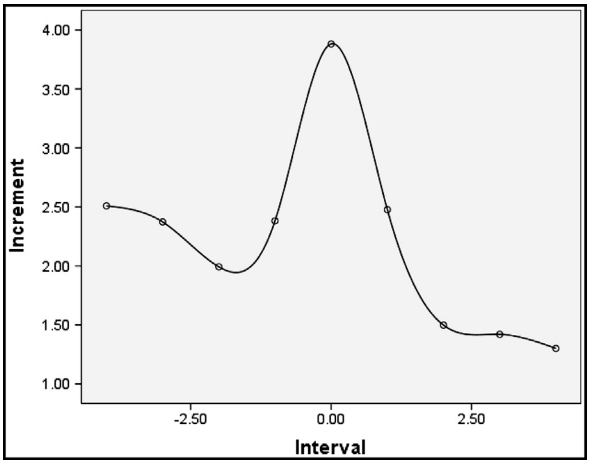

Fig 7. Average mandibular growth curve for girls; 0.00 corresponds to a mean age of 11.50 years.

Table II. Fishman hand-wrist (HW)[37] and cervical vertebral stages (CS): distribution at onset and peak

Maturation stage	Structure	HW Modal stage (%)	HW Range	CS Modal stage (%)	CS Range
Boys					
Onset	Height	1 (30)	1-7	1 (54)	1-5
	Facial composite	2 (31)	1-7	1 (60)	1-4
	Mandibular length	2 (35)	1-7	1 (60)	1-4
Peak	Height	7 (42)	4-10	4 (47)	1-6
	Facial composite	7 (36)	3-10	4 (34)	1-6
	Mandibular length	7 (46)	5-10	4 (38)	1-6
Girls					
Onset	Height	1 (32)	1-6	1 (64)	1-4
	Facial composite	3 (19)	1-8	1 (54)	1-4
	Mandible	2 (21)	1-7	1 (64)	1-4
Peak	Height	7 (30)	3-8	2 (28)	1-5
	Facial composite	7 (36)	3-10	4 (24)	1-5
	Mandible	7 (28)	3-10	4 (30)	1-6

both boys and girls. In boys, predictions generated from the vertebral approaches show uniformly greater errors than predictions generated from average ages and onset in stature. Also, in boys, the error variance of predictions based on mean age is about the same as those based on statural onset. In girls, the predictions generated from mean chronologic ages from the literature and from the vertebral method show greater errors than predictions generated from the onset in height plus 2 years ($\chi^2 = 6.5$; $P < 0.05$).

DISCUSSION

The display of longitudinal data in the form of incremental growth curves began in 1927 when Scammon[38] plotted semiannual height data that Montbeillard had collected from his son's birth in 1759 to his 18th birthday. Since then, a number of workers have drawn incremental growth curves of statural or facial growth in both sexes.[6-10,15,16,21] The average curves generated here are similar; they are almost identical to Scammon's initial curve from a sample of 1.

Table III. Timing at onset and peak: between-measures comparison

Comparison (H_0:δ = 0)	Paired t test: Onset	Paired t test: Peak
Boys		
Height to face	−0.323	−4.121*
Height to mandible	0.321	−3.381†
Face to mandible	0.614	0.120
Girls		
Height to face	−3.816†	−4.238†
Height to mandible	−1.486	−3.656†
Face to mandible	1.439	0.137

*$P < 0.01$; †$P < 0.05$.

Table IV. Age as an index of maturation: variation (root mean squared error between Nanda's average onset ages [12 and 10 y])[15] and actual age of onset

Item	Root mean squared error (y): Boys (age 12)	Root mean squared error (y): Girls (age 10)
Height	0.97	1.20
Facial composite	1.07	1.20
Mandibular length	1.27	1.20

Although the curves for both sexes are generally similar, there is some apparent sexual dimorphism. As has been reported by many others (eg, Nanda,[15] Grave,[8] and Tanner et al[10]), the boys grew more and grew for longer than did the girls. Gasser et al[40,41] reported a prepubertal, or "midgrowth" spurt at approximately 7.5 years of age in both sexes. In our study, a midgrowth spurt was apparent in the average facial and mandibular growth curves of the girls, but not boys. However, cephalograms from the key age—7.5 years—were not included in our sample of boys; hence, this apparent difference cannot be pursued.

Although many similarities were found between our average curves and other growth curves in the literature, a few differences can be noted. Bowden,[9] Tanner et al,[10] and Hägg and Taranger[11] found that the average ages at the onset and peak of pubertal growth in stature are about 12 and 14 years in boys and 10 and 12 years in girls. The data from our sample of boys agree; however, the girls were accelerated by nearly a year: statural onset at 9.3 years and a peak at 10.9 years. The differences between the mean ages of this study and those reported in the literature might be due to secular variations among samples

Table V. Age, hand-wrist (HW) stages, and cervical vertebral stages (CS) as indexes of maturation (peak): correlation (r), root mean squared error (RMSE), and error rank

		Index peak stage		
Item	*Statistic*	*HW stage*	*Nanda[15] means, ages 12 and 14 y*	*CS 3.5*
Boys				
Height	RMSE	1.11	1.01	1.35
	r	0.70*	NA	0.49*
	Rank	2	1	3
Facial composite	RMSE	0.90	1.18	1.35
	r	0.72*	NA	0.44*
	Rank	1	2	3
Mandibular length	RMSE	0.87	1.16	1.27
	r	0.75*	NA	0.52*
	Rank	1	2	3
Girls				
Height	RMSE	0.88	1.46	2.00
	r	0.59*	NA	0.46*
	Rank	1	2	3
Facial composite	RMSE	0.99	1.25	1.71
	r	0.58*	NA	0.41*
	Rank	1	2	3
Mandibular length	RMSE	1.11	1.33	1.82
	r	0.53*	NA	0.33†
	Rank	1	2	3

NA, Not applicable.
*$P < 0.01$; †$P < 0.05$.

drawn from different parts of the world at different times. The Bolton-Brush Growth Study, for example, began in 1927, approximately 20 years earlier than the other collections; however, given the common observation that girls mature earlier today than several generations ago, the acceleration seen here is surprising.[42]

There is disagreement in the literature concerning the relationship between the timing of the spurts in stature and facial size. Nanda[15] and Bambha[6] reported that the face achieves its circumpubertal maximum later than stature, whereas Hunter,[16] Grave,[8] and Bergersen[13] argued that the peaks in stature and the face occur synchronously. Bambha also noted that stature and the face display similar durations of growth during the pubertal spurt. Based on a considerably larger sample, our investigation argues that onset in stature occurs more or less at the same time as onset in the face and the mandible in boys and perhaps a bit earlier in girls. In both sexes, the peak in stature had a shorter duration and tended to occur a few months before that of the face and mandible. Accordingly, statural events might have predictive significance in planning the timing of treatment. Furthermore, these data indicate that the mandible grows synchronously with the rest of the face and does not peak later or grow markedly longer.

Errors in assessing maturation with chronologic age are obvious, even to the untrained eye. It is easy to see that a child is large or small for its age. In our study, the actual age of onset was compared only with mean ages—10 years for girls and 12 years for boys. The root mean squared error—a kind of error standard deviation—for this approach ranged from 12 to 15 months. Given this variation, it commonly is assumed that "skeletal" ages based on ordinal skeletal events must necessarily generate better estimates of a patient's progress toward maturity.[8,9,11-14,17-21,24-28] Furthermore, errors with this approach are not obvious; nobody, for example, says that a child is "small for a CS 2." We did not examine this presumed superiority with respect to onset; however, its individual growth curves allow it to be tested with respect to the achievement of peak velocity.

In boys, the hand-wrist ages displayed a moderately strong relationship to the timing of the peaks in stature, the face, and the mandible; however, the correlations were somewhat weaker in girls, a finding that mirrors a conclusion reached earlier by Smith.[43] As judged by ranking the root mean squared errors, the Fishman hand-wrist assessments had consistently lower errors than either mean chronologic age or vertebral assessments for stature, facial size, and mandibular length.[37] The cervical vertebral stages showed only a weak to moderate relationship to the timing of peak growth and had consistently the greatest root mean squared errors. These results suggest that hand-wrist staging might be of value in assessing a patient's maturation. However, the errors relative to mean chronologic age standards were only a few months greater than those seen with the Fishman system.

Indexes of maturation might provide a rough assessment of a patient's current state of development; however, a predictor of future growth would be of greater utility to the orthodontist.

The literature shows that peak normally follows onset by about 2 years[6-11]; therefore, statural onset plus 2 years was used here to predict the peak of the pubertal growth spurt. Our findings indicate that, at least for girls, a pubertal spurt duration of about 2 years is quite accurate. Rankings based on root mean squared errors showed a significant ($P < 0.05$) difference among methods, with onset of the spurt in stature plus 2 years as the best predictor of the peak in pubertal growth. Accordingly, statural onset plus 2 years also showed a moderately high, statistically significant correlation with the time of the actual peak of facial growth. Boys

Table VI. Height, age, and cervical vertebral stage (CS) as predictors of facial growth peak: root mean squared error (RMSE [y]) and correlation (r) between predicted and actual peak ages

		Prediction Method				
				CS 2		
Item	*Statistic*	*Height onset + 2 y*	*Nanda[15] means, ages 12 and 14 y*	*CS 2 + 1 y*	*CS 2 + 1.5 y*	*CS 2 + 2 y*
Boys						
Facial composite	RMSE	1.10	1.18	1.96	1.83	1.84
	r	0.54*	NA		0.3†	
	Rank	1	2		3	
Mandibular length	RMSE	1.17	1.16	1.96	1.83	1.84
	r	0.45*	NA		0.29†	
	Rank	2	1		3	
Girls						
Facial composite	RMSE	0.93	1.25	1.74	1.81	2.00
	r	0.67*	NA		0.17	
	Rank	1	2		3	
Mandibular length	RMSE	1.27	1.33	1.98	2.05	2.23
	r	0.44*	NA		−0.04	
	Rank	1	2		3	

NA, Not applicable.
**P* <0.01; †*P* <0.05.

had an interval of approximately 2.5 years between onset and peak, a finding suggesting that statural onset plus 2.5 years might be a better prediction of their facial growth peak. Mean chronologic age, however, had errors that were almost as small.

On balance, these data imply that the use of contemporary measures of skeletal age adds little to the prediction of timing, given that our results show that indexes of maturation and chronologic age have similar error variations (root mean squared error of about a year) in both assessing the current state of maturation and predicting the timing of peak growth. Great among-stage variability was seen in the hand-wrist and cervical vertebral methods, both at onset and at peak. This variation might be due to differences in the rate of development among individuals or because of technical errors in the evaluation of an annual radiograph. Franchi et al[44] reported that the vertebral stages occur approximately 1 year apart—a suggestion that could not be verified here. Many subjects progressed through multiple hand-wrist and vertebral stages in 1 year, whereas others took several years to advance by 1 stage. Fishman[37] also observed this phenomenon, noting that each child has a time schedule of development that varies in both acceleration and deceleration.[21]

The literature argues that the vertebral stages correlate well with those of hand-wrist film and thus, by inference, should support an assessment of individual facial skeletal maturation.[22-24,26,28,29,32] Be that as it may, the cervical vertebral method as applied here had the largest error standard deviations in both the assessment of maturation and the prediction of the peak, an outcome that mirrors that of Bernard,[30] whose sample also came from the Bolton study. The lack of accuracy seen here could be due to a limited number of stages, a blurred distinction between stages (the characteristics of one stage frequently overlap those of adjacent stages), and the subjectivity of the process of vertebral staging. To control technical error, we used the method of San Román et al[26] to measure the concavity at the lower border of the vertebrae. Furthermore, staging was done in parallel by 2 people. Ultimately, however, the problem might not be one of reliability but, rather, of validity: namely, an intrinsic lack of predictive power.

Another source of error in the hand-wrist and vertebral indexes is their reliance on annual or biennial radiographs to assess a subject's development. When an event is first seen on a radiograph, it is assumed to have occurred at the midpoint of the previous interval, an assumption that generates a built-in error standard deviation of about 4 months for annual records. This error not only is unavoidable, but also likely to become worse: radiographs probably never again can be taken frequently for assessing maturation, especially if the method is known to be relatively crude and unreliable. In contrast, a patient's height can be measured more often than once a year. It might be possible to plan the timing of treatment based on serial measurements of stature taken at home and reported to a practice's Web site. The error of the statural method—already the lowest of the prediction methods studied here—perhaps can be decreased to yield even better definitions of the onset and the peak of the facial growth spurt, an event that can serve as a rational basis for deciding not whether to treat early or late for everyone but, rather, attempting to treat at the right time for the patient.

CONCLUSIONS

This investigation is perhaps the most extensive study of the pattern of facial growth and its relationship to various common maturity indicators. Its longitudinal nature allowed us to construct growth curves on which the age of onset and peak of the pubertal growth spurt in height, facial size, and mandibular length could be identified for each of the 100 subjects. We concluded that the vertebral and hand-wrist measures of skeletal age studied here offer no marked advantage relative to chronologic age, in either assessing or predicting the timing of facial growth. ("How old are you? Can you predict when you are going to be 10? You can? Come in and see me then.") Furthermore, we suggest that stature, because it can be measured repeatedly without side effects, might be an even more clinically useful predictor than age.

We thank Heidi Israel, associate professor, Department of Orthopaedic Surgery at Saint Louis University, for her invaluable statistical assistance during this investigation and Mark Hans and the staff of the Bolton-Brush Growth Study Center for giving us access to the records used here.

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