Maturational Patterns and Prediction During Adolescence

Leonard S. Fishman

A mixed longitudinal study of Skeletal Maturation Indicators (SMI) from the hand-wrist radiograph as a means for evaluating maturational status.

KEY WORDS: • Hand-wrist Radiograph • Maturation • • Skeletal maturation • X-ray •

Maturational development embodies the overall biologic progression through life. In the growing years, indicators of the level of maturational development of the individual provide the best means for evaluating biologic age and the associated timing of skeletal growth. Adolescence is a period demonstrating varying increments of skeletal change occurring in widely disparate age periods.

It has been clearly demonstrated that chronologic age alone provides little insight or validity for identifying the stages of developmental progression through adolescence to adulthood (Johnston et al. 1965, Hunter 1966, Brown 1972, Tofani 1972, Fishman 1979 and 1982, Houston 1980, Hagg 1982). The common practice of comparing an individual's cephalometric measurements to chronologically based "normal" standards provides no biologically sound basis for growth evaluation, prediction or treatment timing. However, appropriate maturational ages can provide an accurate indication of development, and may be used as a means for making comparisons between children.

Variations in relative statural and craniofacial growth velocities are directly related to differences in maturational development, and stages of relative maturation are directly associated with specific amounts of completed growth (see all references).

Maturational development can be accurately assessed, but there are no norms that can be assigned on a simple chronologic basis. Every child demonstrates a unique sequential pattern of events, and generalized descriptions of the sequence of maturational stages and associated skeletal growth curves that represent the general population cannot be directly associated in any accurate manner with a specific individual of either sex.

Author Address:

Dr. Leonard S. Fishman
550 East Genesee Street
Syracuse, NY 13202

Dr. Fishman is in the private practice of orthodontics in Syracuse, New York. He also serves as a Clinical Associate in the Graduate Department of Orthodontics, Eastman Dental Center, Rochester, New York. He holds a D.D.S. degree from Temple University School of Dentistry in Philadelphia, and a Certificate in Orthodontics from the Eastman Dental Center.

Validity of the concept of "normal skeletal age" is considered by the Author to be too questionable for guidance in clinical decisions.

The system of Skeletal Maturation Assessment (SMA) has been presented as a more reliable means of utilizing hand-wrist radiographs for this purpose (FISHMAN 1982). Eleven Skeletal Maturity Indicators (SMI's) have been previously outlined and described:

Skeletal Maturity Indicators (SMI)

Epiphysis as wide as diaphysis

1. Third finger-proximal phalanx
2. Third finger-middle phalanx
3. Fifth finger-middle phalanx

Ossification

4. Adductor sesamoid of thumb

Capping of epiphysis

5. Third finger-distal phalanx
6. Third finger-middle phalanx
7. Fifth finger-middle phalanx

Fusion of epiphysis and diaphysis

8. Third finger-distal phalanx
9. Third finger-proximal phalanx
10. Third finger-middle phalanx
11. Radius

These provide a methodical approach to identifying specific maturational stages that cover the entire adolescent period. These SMI's pertain to developmental changes involved in the osseous processes of widening of epiphyses, ossification, capping of epiphyses, and epiphyseal-diaphyseal fusion.

As seen above, SMI's 1-3 and 5-7 are based on selected areas of the third and fifth fingers. SMI 4 is based on the ossification of the adductor sesamoid of the thumb, and 8-11 on fusion of selected areas of the third finger and the radius.

The SMI's typically occur at earlier chronologic ages for girls, but in both sexes they exhibit a rather even chronologic distribution from the initiation to the termination of adolescence. The SMI's make it possible to judge an individual's relative timing of maturation — whether it is early, average, or late.

Comparison of boys and girls on a maturational time-scale shows no sexual differences in the percentages of completed incremental growth at the same SMI levels, regardless of chronologic age (Fishman, 1982).

A positive association exists between the stage of maturation and the velocity of growth. Comparison of individual maturation patterns also reveals positive correlations between maturation levels and accelerations or decelerations in growth rate. Maturation is clearly the common denominator between individuals in relation to the timing and amount of incremental skeletal growth and the velocity of growth, regardless of sex or chronologic age.

The purpose of the present investigation is twofold. The first is to more clearly define the interrelationships between early, average and late maturation relative to changing maturational patterns during adolescence. The second is to assess the feasibility of predicting these maturational patterns with a significant degree of reliability. Such basic information is considered essential to a more biological and clinically defensible approach to craniofacial growth evaluation, growth prediction and treatment planning.

— Sampling and Methods —

Some unique criteria are required for sampling clinical records for maturational studies. Secular factors can disadvantageously increase the variability of the data, and a very large cross-sectional database can greatly reduce these effects. A large database also makes it possible to significantly shorten the time frames, thus decreasing the effects of variation of maturational age within subgroups. The reliability of statistical results relating maturational data to chronologic age is especially enhanced with a large database of longitudinal records.

This investigation is planned to closely conform to those sampling requirements. As seen in Table 1, a large cross-sectional sample of 4,000 data records was randomly assembled from the author's private practice. These included 2225 hand-wrist radiographs of females and 1775 of males. The System of Skeletal Maturation Assessment (SMA) was applied to each film, and the appropriate Skeletal Maturation Indicator (SMI) assigned.

Separate female and male data files associated with each SMI were extracted from the total database. The average number of data records for each SMI was 202 for the girls and 161 records for the boys.

Within this large database were longitudinal samples that included a series of two or more individual patient records. Longitudinal samples were selected on the basis of specific rates of maturation (late, average, or early). Computations were accomplished with existing software supplemented by customized programming.

— Results —

Data records associated with each of the eleven SMI's for each sex were statistically evaluated to establish mean chronologic age values and the associated standard deviations from those mean values. Chronologic age values deviating by one standard deviation or more were considered either late or early relative to their respective levels of maturation. This allows for the immediate typing of an individual as being maturationally early, average, or late.

Four maturational categories were then established, identified as relative levels A through D. Levels A and D represent early and late maturers respectively, deviating from the mean by more than one standard deviation. Those within one standard deviation of the mean were further divided on the basis of the direction of the deviation, B for those earlier than the mean, and C for those later than the mean (Tables 2 and 3) (Figs. 1 and 2).

It is of interest to note that for both sexes a rather smooth and even progression of SMI stages exists throughout the entire adolescent period. Since most children fall within the overall average rate of maturation, the subgrouping into relative levels B and C provides additional insight and an opportunity to further examine maturational patterns for this large group. The maturation charts

Table 1

SMI Database
Number of Records

SMI	-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	Total
Female	115	93	86	106	154	243	304	216	183	447	278	2225
Male	183	135	111	131	147	261	251	115	106	213	122	1775

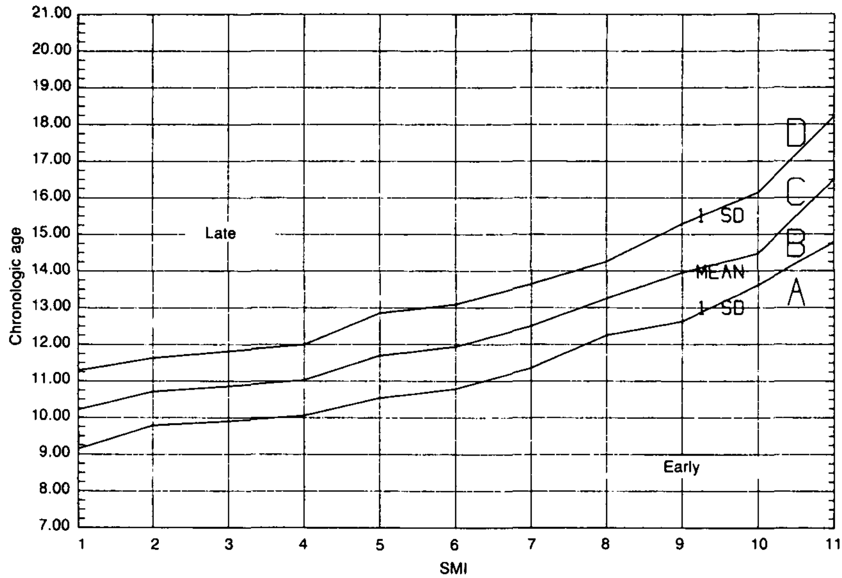

Fig. 1 Levels of maturation, FEMALE

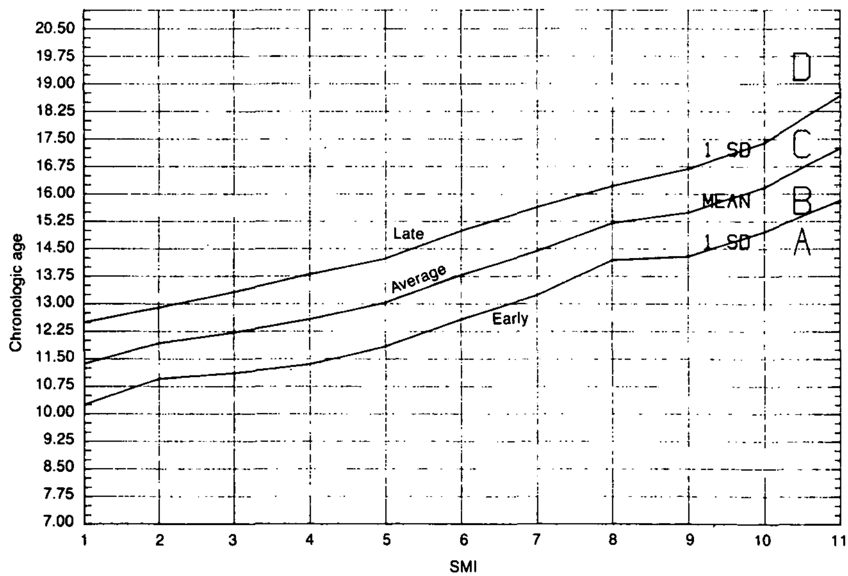

Fig. 2 Levels of Maturation, MALE

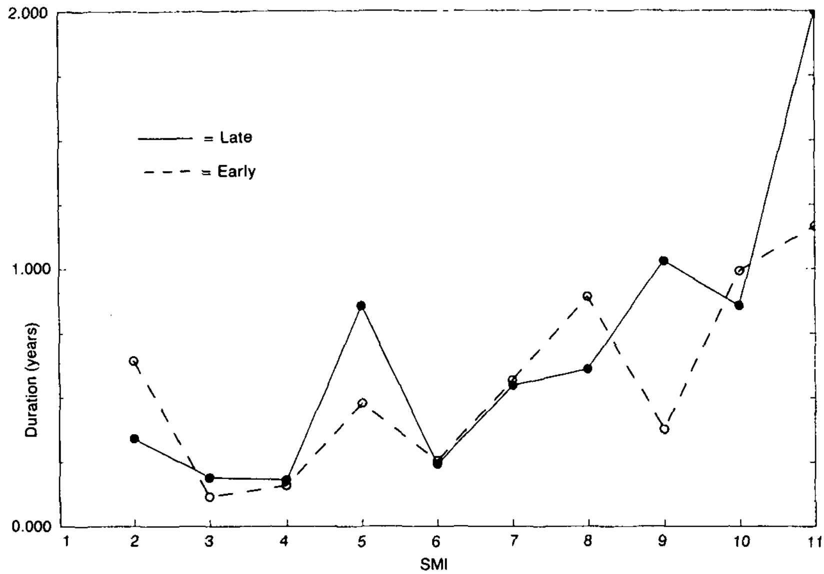

Fig. 3 Duration of SMI's in early and late maturers, FEMALE

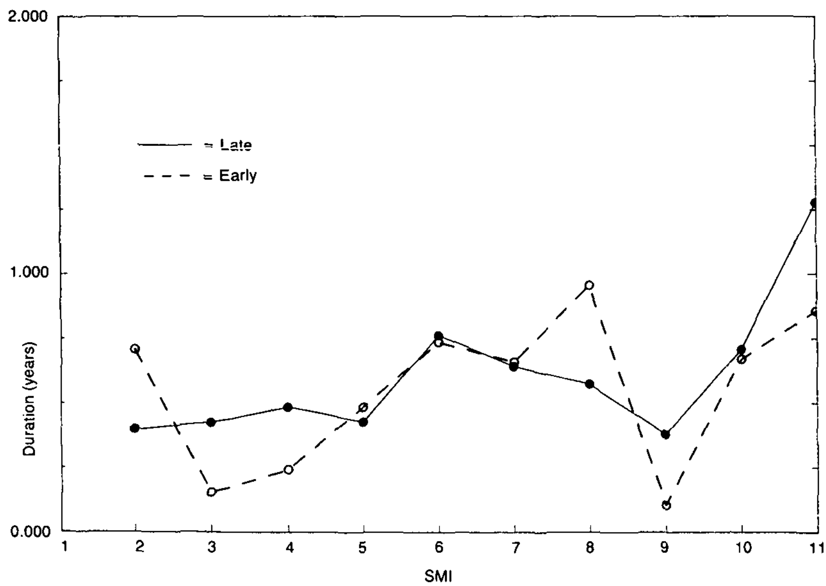

Fig. 4 Duration of SMI's in early and late maturers, MALE

facilitate the plotting, and provide visual representation of individual maturational patterns.

Since late and early maturers demonstrates large chronologic age differences within each SMI stage, the average time period between successive SMI stages was investigated. Do early maturers achieve their maturational changes faster than late maturing children? Figs. 3 and 4 demonstrate the average chronologic time periods between SMI stages for the girls and the boys.

It is readily evident on initial inspection that variations in the duration of SMI periods for the two groups are associated with the adolescent period. Some SMI maturation periods exhibit longer time intervals for late maturers, and some demonstrate the opposite pattern, although not to the same degree. Closer inspection of the female and male groups reveals exceptionally similar patterns for the early groups.

Early maturers of both sexes exhibited almost identical SMI duration values for SMI's 1-5 and 7-11. The only significant difference in SMI duration for the early group is between SMI 5 and 6. It has been previously demonstrated that girls in general reach the point of peak velocity of growth at SMI 5, and boys at SMI 6. This may be the reason for this isolated exception to correlation between the sexes.

For the late maturation groups, considerably less correlation is found between the female and male groups, although the duration of time between SMI's 1-2 and 10-11, at the beginning and end of the adolescent period, are very similar.

In regard to the comparisons of late periods with early periods, the female late group exhibits significantly longer time between SMI periods 4-5, 6-9, and 10-11. The male late group exhibited longer time periods between SMI 2-4, 9-10, and 10-11.

Both female and male early groups demonstrate significantly longer periods only between SMI stages 1-2 and 7-8. The balance of the late and early SMI periods were generally similar.

To further demonstrate the relationship between chronologic time and rates of maturation, the female and male sam-

Table 2

Average Age at each SMI
for Early, Average and Late Maturers
FEMALE

SMI	Early	Average	Late
1	9.157	10.230	11.302
2	9.800	10.722	11.643
3	9.914	10.872	11.831
4	10.072	11.041	12.011
5	10.549	11.708	12.867
6	10.802	11.955	13.108
7	11.369	12.512	13.655
8	12.260	13.263	14.265
9	12.636	13.967	15.298
10	13.626	14.890	16.154
11	14.791	16.508	18.225

Table 3

Average Age at each SMI
for Early, Average and Late Maturers
MALE

SMI	Early	Average	Late
1	10.248	11.368	12.488
2	10.955	11.921	12.887
3	11.109	12.211	13.312
4	11.351	12.574	13.797
5	11.835	13.029	14.224
6	12.571	13.779	14.987
7	13.230	14.429	15.629
8	14.185	15.194	16.203
9	14.289	15.485	16.682
10	14.958	16.174	17.390
11	15.815	17.242	18.669

ples were each divided into three SMI subgroups, 1-4, 4-7, and 7-11. Those data records that included the time between stages 1 and 4 presented a period of accelerating growth velocity. The second group, between stages 4 and 7, presented children with periods of exceptionally high-velocity skeletal growth, and included periods of intense acceleration, peak velocities, and intense deceleration of growth. The third SMI period, 7-11, presented decelerating growth rates.

As seen on Figs. 5 and 6, grouping in this fashion demonstrated additional differences between the late and early maturers. The female late maturers maintained high velocity for longer durations of time (SMI 4-7). They also stayed longer in the period of decelerating velocity (SMI 7-11), as well as in the total adolescent maturational period (SMI 1-11).

The female early maturers demonstrated longer time periods only during the accelerating growth rate period (1-4).

The male group (Fig. 6) demonstrated longer time periods for the late maturers in the accelerating (SMI 1-4), decelerating (7-11), and total adolescent time periods (1-11). No significant difference was demonstrated in the intervening high growth rate period (SMI 4-7). Boys demonstrated longer time periods for the late, average and early maturers between SMI stages 1-7, but considerably shorter maturation times during later adolescence between stages 7 and 11.

The overall time for the entire adolescent period was considerably less for both average and late maturing boys. This difference is contrary to what has been commonly accepted as fact, and again demonstrates the importance of examining time frames based on maturation rather than simple chronologic time.

It also demonstrates the importance of distinguishing between amounts of growth per chronological unit and growth over a maturational period. Growth in each maturational period is most closely related to ultimate total growth.

The early boys and girls both exhibited similarly shorter overall durations of time, but the average and late boys still demonstrated shorter adolescent time frames than the average and late females.

Maturational progression often remains within the same relative rate — early, average, or late — during extended periods of time and often throughout the entire adolescent period. However, when individual maturational patterns are plotted on the rate-of-maturation chart, as in Fig. 7, it becomes evident that one's progression through adolescence may involve a shift from one relative maturational rate to another.

Although predictable maturational patterns of development cannot be expected, it was considered important to investigate the possibility of revealing patterns that exist on a longitudinal basis within each of the four maturational rates (A, B, C, D) that were sufficiently valid to be used for future maturational estimation. Effects of biological variation were reduced by separating the total investigation sample into the smaller maturational rate samples.

As seen on Tables 4 and 5, female and male longitudinal searches were conducted within the total SMI database. The total sample was initially divided into three groups. Individuals exhibiting SMI stages 1-3 represented the accelerating velocity group. Children in stages 4-7 represented the very high growth velocity group, and 8-11 the decreasing velocity period.

Individuals with only one data record were eliminated from the database used for this part of the study. The remaining subjects, with two or more data records, represented a mixed longitudinal series.

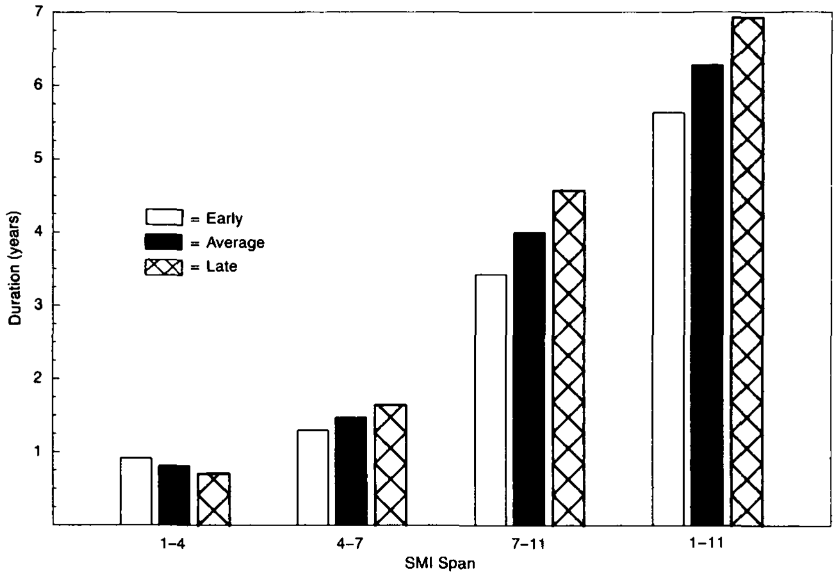

Fig. 5 Length of maturation periods, FEMALE

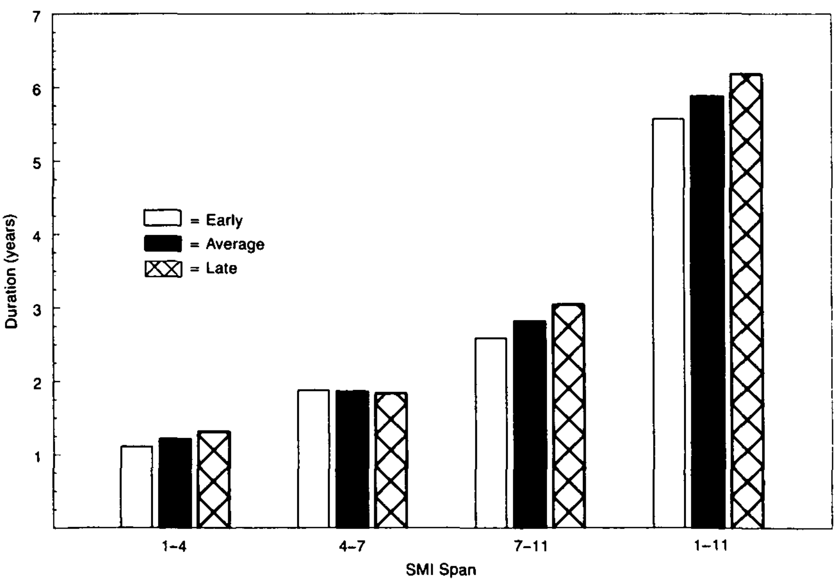

Fig. 6 Length of maturation periods, MALE

The female longitudinal sample included 421 children and 907 data records, the male sample 338 children and 808 data records.

Each of the girls and boys with records exhibiting SMI 1-3 was categorized into one of the four relative levels of maturation, and their respective chronologic ages recorded. The associated follow-up chronologic age at the higher SMI stage was then recorded for each individual, and mean chronologic values established in a progressive manner. As each new chronologic SMI stage was established, additional children displaying similar chronologic and SMI stages were identified and followed through their higher values.

In this manner, four maturational paths were established for each sex, representing the longitudinal progression of maturation for children who initiated adolescence at each of the four different chronologic levels. Each path was represented by eleven points associated with their respective SMI chronologic age values.

To see whether maturational prediction could be responsibly accomplished, each of the eight data arrays were subjected to both first-order and polynomial curve fitting. In each case, a least-squares curve fit was performed on seven different types of equations by solving two equations simultaneously using Cramer's rule (Table 6).

Polynomial curve fits and the least-squares method were also calculated for orders 1 through 3. Because of the higher order of equations, they were solved with a modified Gauss-Jordan method with pivot strategy.

Correlation coefficients were calculated to establish the degree of fit for each of the nine equations as applied to each of the four sets of longitudinal data for female and for male subjects. All of the data arrays for both sexes demonstrated excellent linear, exponential and hyperbolic #2 first-order curve fits and excellent polynomial order 2 and order 3 curve fits (Table 6). Correlation coefficients for all of these curves were above 0.92.

Fig. 8, which is closely representative of all the curve-fit findings for all levels and both sexes, shows the closest fits for the exponential, hyperbolic 2 and third-order polynomial curves. The third-order polynomial curve always demonstrated an exceptionally high degree of fit, so it was selected to represent the longitudinal curves. The four female and four male polynomial curves were each constructed from 31 sets of SMI chronologic age data points, and were subsequently tested as maturation prediction curves.

Table 4

Female Longitudinal Search
Longitudinal SMI Data-base
Number of Records

SMI>	1-3	4-7	8-11
Level A	56	98	63
Level B	79	171	62
Level C	80	134	56
Level D	23	50	35

Total Number of Patients = 421

Total Number of Data Records = 907

Table 5

Male Longitudinal Search
Longitudinal SMI Data-base
Number of Records

SMI>	1-3	4-7	8-11
Level A	75	100	15
Level B	132	128	28
Level C	116	85	33
Level D	47	39	10

Total Number of Patients = 338

Total Number of Data Records = 808

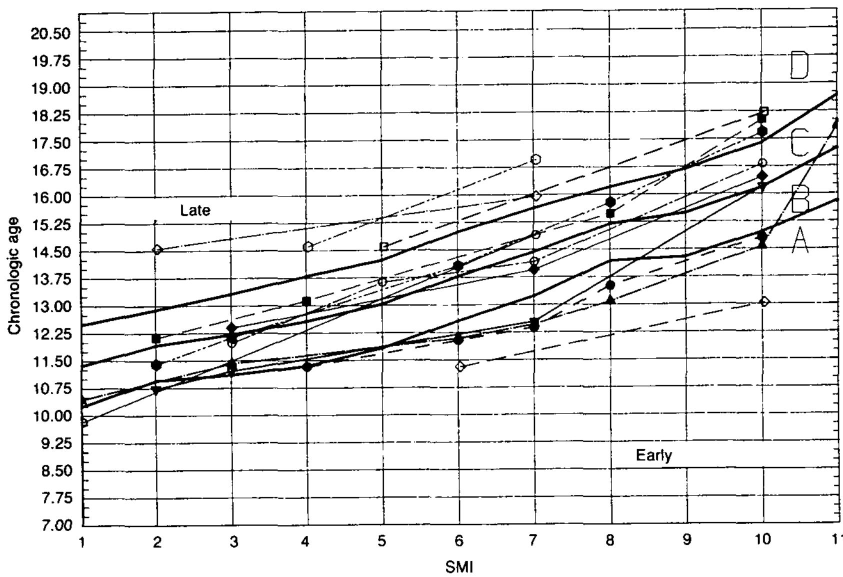

Fig. 7 Maturational variations

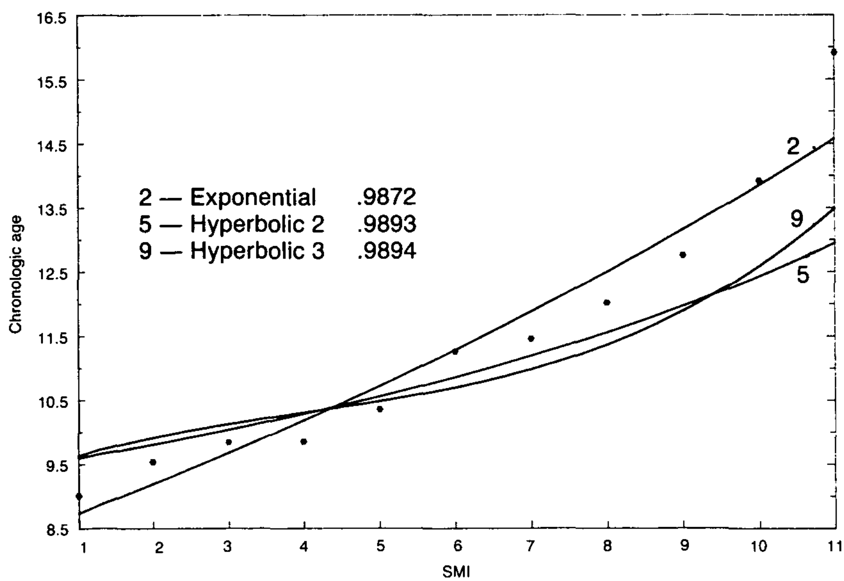

Fig. 8 Mathematical curve fits, female maturation level A

Very close similarities exist between the curvilinear regression curves for females and males (Figs. 9 and 10).

For both sexes, the early (level A) curves remained within their boundaries or close to the border of level B until SMI stage 8, at which time the A curve entered well within the B range (within one SD of average), approaching the mean values for their respective total samples.

Those with late maturation (level D) also exhibited similarities between the male and female sample, in that the curves did not regress toward the total sample mean values until SMI 10, late in the adolescent period for both sexes.

Those with near-average maturation (B and C) maintained a consistency in their maturational progress, not departing outside their respective boundaries. Toward the end of the maturation period these two curves regressed even closer to the mean values.

To test the reliability of these curves for prediction, randomly selected longitudinal SMI records of 184 female and 187 male individuals were organized to represent all significant testing possibilities. A total of 742 tests were performed, evenly distributed among the four female and four male curves (Fig. 11). These represented tests of the following SMI groups:

within the —

accelerating growth velocity period (1-4)
high growth velocity period (4-7)
decelerating velocity period (7-11)

and *between* the periods of —

acceleration (1-4) and high velocity (4-7)
high velocity (4-7) and deceleration (7-11)
acceleration (1-4) and deceleration (7-11)

In this way. all possibilities were tested. Future SMI stage values and future chronologic ages values were estimated for all of these examples and tabulated.

As mentioned previously, biologic prediction cannot be an exact science. The objective in this investigation was to examine the degree of reliability available, and to determine whether prediction could be utilized in a responsible way.

As seen on Tables 7 and 8, the female and male SMI prediction errors are very similar when examined either on the basis of the six SMI groups or by grouping by one of the four rates of maturation. An average of over 80% of all of the estimations were correctly made within the range of the SMI stage. This is considered very high for biologic prediction. The decelerating velocity period (SMI 7-11), and the accelerating vs. decelerating period predictions (SMI 1-4 vs SMI 7-11) exhibited the highest degree of reliability for both sex groups (over 90%).

For maturation rates, the highest levels of predictability were found for rates A, B, and C in the female sample, and rate B in the male sample. Test periods involving high growth velocity seem to

Table 6

Curve-fitting

Formula	sex
First-order Curvefits	
1. Linear $Y=A+BX$	FM
2. Exponential $Y=A(e^{BX})$	FM
3. Power $Y=A(X^B)$	M
4. Hyperbolic #1 $Y=A+B/X$	FM
5. Hyperbolic #2 $Y=1/(A+BX)$	FM
6. Hyperbolic #3 $Y=X/(A+BX)$	FM
7. Logarithmic $Y=A+BLogX$	FM
Polynomial Curvefits	
8. Order 2 $Y=K+AX+B(X^2)$	FM
9. Order 3 $Y=K+AX+B(X^2)+C(X^3)$	FM

$r>0.92$ for all Curvefits

Table 7

SMI Prediction Errors
Female

SMI→	1-4>1-4	1-7>4-7	7-11>7-11	1-4>4-7	4-7>7-11	1-4>7-11
0	41.7%	21.9%	53.1%	31.3%	31.3%	40.6%
<1	83.4%	75.0%	93.7%	68.8%	81.3%	90.6%
1	41.7%	53.1%	40.6%	37.5%	50.0%	50.0%
>1	16.6%	25.0%	6.3%	31.2%	18.7%	9.4%

	Level A	Level B	Level C	Level D
0	50.0%	25.0%	35.4%	35.0%
<1	81.3%	85.4%	83.3%	75.0%
1	31.3%	60.4%	47.9%	40.0%
>1	18.7%	14.6%	16.7%	25.0%

Table 8

SMI Prediction Errors
Male

SMI→	1-4>1-4	1-7>4-7	7-11>7-11	1-4>4-7	4-7>7-11	1-4>7-11
0	28.6%	25.8%	40.6%	28.1%	28.1%	43.8%
<1	75.0%	74.2%	90.6%	81.2%	75.0%	90.1%
1	46.4%	48.4%	50.0%	53.1%	46.9%	46.9%
>1	25.0%	25.8%	9.4%	18.8%	25.0%	9.3%

	Level A	Level B	Level C	Level D
0	22.9%	35.4%	34.8%	37.8%
<1	72.9%	93.7%	78.3%	80.0%
1	50.0%	58.3%	43.5%	42.2%
>1	27.1%	6.3%	21.7%	20.0%

Table 9

Average Chronologic Age Range
of Prediction Errors
(Years in decimal values)

SMI→	1-4>1-4	1-7>4-7	7-11>7-11	1-4>4-7	4-7>7-11	1-4>7-11
Female	.246	.246	.363	.653	.431	.336
Male	.603	.399	.272	.421	.302	.515

	Level A	Level B	Level C	Level D
Female	.496	.420	.289	.326
Male	.423	.342	.341	.410

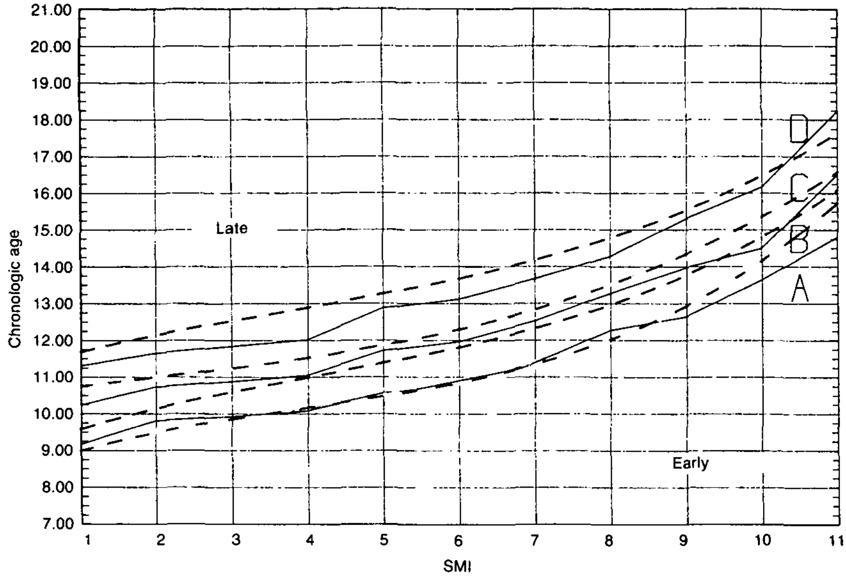

Fig. 9 Levels of maturation, FEMALE

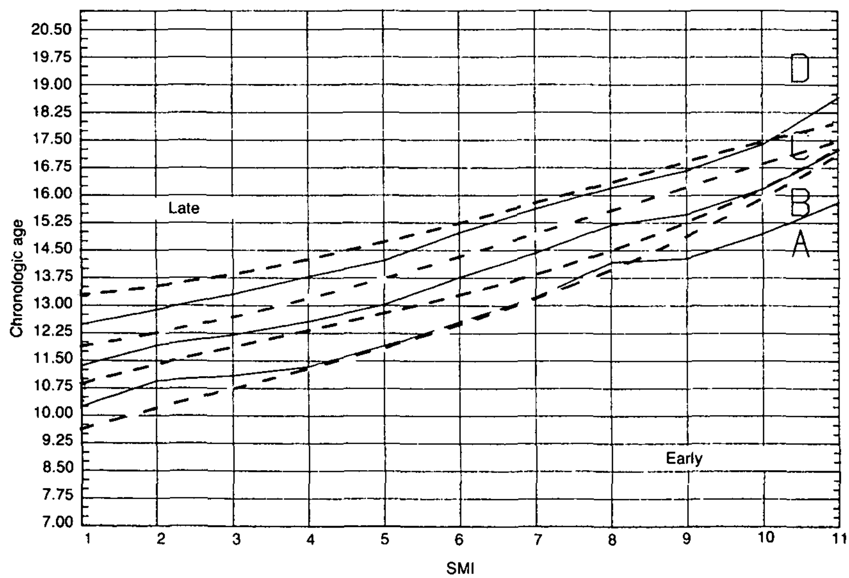

Fig. 10 Levels of maturation, MALE

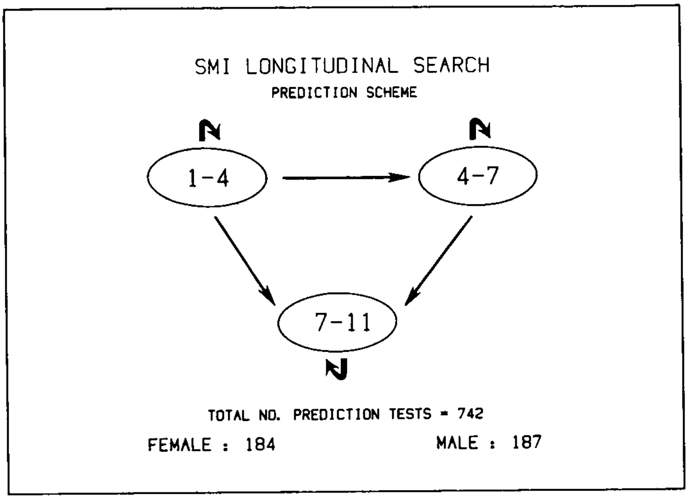

Fig. 11
SMI longitudinal search prediction scheme

yield somewhat lower predictive reliability, while periods involving a deceleration in growth velocity seem to exhibit more predictive reliability.

As seen on Table 9, the chronologic age predictive errors reveal equally encouraging results. Almost all of the SMI and maturation rate subgroups demonstrate a mean chronologic error between three and five months. No consistent patterns emerged from comparing the subgroups to each other, or from comparisons between the girls and boys.

Utilizing the proper prediction curve, SMI values can be predicted within one maturational stage value more than 80% of the time. Chronologic age values can be predicted within approximately five months or less.

— Summary —

If utilized properly, hand-wrist radiographs provide a reliable and efficient means of developmental assessment. Simple reference to a hand-wrist radiographic atlas is not as reliable if it includes an assumption that individual's chronologic age predetermines the normality of the related skeletal age. In the Author's opinion, this is a misapplication of the concept of skeletal age; a *"normal"* skeletal age for a specific chronologic age is not a reasonable indicator of developmental normality.

This investigation and others have clearly shown that healthy children of any age do not demonstrate any chronologic specificity regarding particular stages of maturation. Identifiable maturational indicators provide a more reliable means of evaluating individualized maturational levels within the very wide chronologic age ranges demonstrated by normal growing children.

Maturational patterns and factors related to the timing of these patterns are more clearly revealed if examined on a basis of whether they are associated with late, average, or early developmental periods. This information provides the clinician with the facts and tools to better

correlate treatment planning with individualized growth expectations. The selection of specific treatment procedures and their timing can then be facilitated in a very practical way.

Orthodontists have long used cephalometric and other associated information to analyze skeletal morphology and directional growth patterns for individual patients. Individualized evaluation and prediction of the timing of these changes has not been achieved, and it is not valid to base treatment decisions on very general total population data. Each individual expresses growth velocity patterns and incremental increases in growth amounts that are specific and unique for that person, and it is extremely unlikely that any child would demonstrate a growth velocity curve that conformed to that exhibited by the total population.

Maturational information does provide an opportunity to markedly improve on such evaluations.

It is very important to clearly identify basic factors that represent different entities to avoid erroneous interpretations. This has led to a great deal of confusion in the past. For instance, *boys do not take a longer time to mature.* They simply do it at a later chronologic age; the period of male adolescence generally lasts no longer than female adolescence.

The literature is saturated with statements that present "facts" such as "a girl starts growing at approximately age 10, reaches peak velocity of growth at age 12 and terminates growth at approximately age 14." Such assumptions, for girls or boys, are particularly inaccurate and misleading when applied to an individual child. The classic growth curves illustrating such statements are no more than statistical representations of data that average the total population of all boys or all girls. These curves do not even hint at the innumerable individual variations in the underlying data.

The late mandibular growth spurts often attributed only to boys show a sex difference only with chronological measurement. On a maturational scale, boys do not demonstrate any extensive differences from girls in the length of incremental growth periods. They are just simply older on the calendar when these stages occur.

Further clarification is still needed on these and many related points of confusion. AO

REFERENCES

Bambha, J. K. 1961. Longitudinal cephalometric roentgenographic study of the face and cranium in relation to body height. *J. Am. Dent. Assn.* 63: 776-779.

Bayer, L. M. and Bayley, N. 1959. *Growth Diagnosis.* Univ. of Chicago Press, Chicago.

Bergersen, E. O. 1972. The male adolescent facial growth spurt: Its prediction and relation to skeletal maturation. *Angle Orthod.* 42:319-338.

Björk, A. and Helm, S. 1967. Prediction of the age of maximum pubertal growth in body height. *Angle Orthod.* 37:135-143.

Brown, T. 1970. Skeletal maturity and facial growth assessment. *Austral. Orthod. J.* 3:80-87.

Burstone, C. J. 1963. Process of maturation and growth prediction. *Am. J. Orthod.* 49:907-919.

Fishman, L. S. 1979. Chronological versus skeletal age, an evaluation of cranio-facial growth. *Angle Orthod.* 49:181-189.

Fishman, L. S. 1982. Radiographic evaluation of skeletal maturation, a clinically oriented study based on hand-wrist films. *Angle Orthod.* 52:88-112.

Grave, K. C. and Brown, T. 1976. Skeletal ossification and the adolescent growth spurt. *Am. J. Orthod.* 69:611-619.

Hagg, V. 1982. Maturation indicators and the pubertal growth spurt. *Am. J. Orthod.* 82:299-309.

Houston, W. J. B. 1980. Relationships between skeletal maturity estimated from hand-wrist radiographs and the timing of the adolescent growth spurt. *Europ. J. Orthod.* 2:18-93.

Hunter, C. J. 1966. The correlation of facial growth with body height and skeletal maturation of adolescence. *Angle Orthod.* 36:44-54.

Johnston, F. E., Hufham, H. P., Moreschi, A. F. and Terry, G. P. 1965. Skeletal maturation and cephalofacial development. *Angle Orthod.* 35:1-11.

Krogman, W. M. 1979. Maturational age of the growing child in relation to the timing of statural and facial growth at puberty. *Transactions and Studies of the College of Physicians of Philadelphia* 1:32-42

Nanda, R. S. 1975. The rates of growth of several facial components measured from serial cephalometric roentgenograms. *Am. J. Orthod.* 41:658-673.

Singh, J. J., Savara, B. S., and Miller, P. A. 1967. Interrelations of skeletal measurements of the face and body in preadolescent girls. *Growth.* 31:119-131.

Tanner, J. M., Whitehouse, R. H., Marshall, W. A., Healy, M. J. R., and Goldstein, H. 1975. Assessment of Skeletal Maturity and Prediction of Adult Height: TW2 Method. *Academic Press.* London.

Tofani, M. I. 1972. Mandibular growth at puberty. *Am. J. Orthod.* 62:176-195.