Radiographic Evaluation of Skeletal Maturation

A Clinically Oriented Method Based on Hand-Wrist Films

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A system for the evaluation of skele-tal maturity from hand-wrist radio-graphs is developed and presented with complete details for implemen-tation in clinical practice.

The clinical importance of evaluat-ing skeletal maturation has long been recognized by the health professions. Skeletal maturation is an integral part of individual patterns of growth and development. Genetic and acquired abnormalities often lead to deviations in maturation. Secular trends are also evident, with successive generations becoming taller and reaching puberty at earlier ages.

Maturational variations are closely associated with variations in the tim-ing and magnitude of growth.[1-8,16-18] This study deals with the evaluation of skeletal maturation, and presents a system for clinical implementation of such an assessment.

Hand-wrist radiographs have been used for this purpose in many ways by many different investigators. The underlying premise is that the osseous changes seen in the hand and wrist are indicators of more general skeletal changes.

The concept of skeletal or bone age based on the hand-wrist film has been developed so that it can be compared with the individual's chronologic age.

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One approach is based on identification of a limited number of maturational indicators representing ossification events or stages of bone development for each age level. Another technique is to create a composite score based on osseous stages and events at each age level. Most skeletal age standards have been established at annual or semiannual intervals.[9-17,20,23,39]

Most investigators have found significant correlations between maturational stages derived from hand-wrist radiographs and changes in statural height. In general, those studies compared indicators of skeletal maturation stages with one or more levels of adolescent growth, such as the onset, peak or termination of maximum growth velocity. The majority of studies have placed the greatest significance on correlations found close to the time of maximum growth velocity.[20,23]

Correlations between facial growth and general skeletal growth have also been studied. In general, positive correlations have been found at most levels of maturation, particularly in relation to mandibular changes.[19,29] A frequent observation has been that the maximum rate of circumpuberal facial growth occurs slightly later than peak growth in statural height.

Variations in the timing and in the concurrent velocities of statural and facial growth were found to be related to variations in the level of maturational development. Individuals who demonstrated delayed or accelerated maturational schedules exhibited comparable delays or accelerations in skeletal and facial growth.[19,24-25,30-31]

Some negative correlations have also been found.[18,32-34] Differences in research design, particularly where the method of assessment could influence the predictive ability, account for most differences in conclusions. The selection of facial measurements can be a critical factor in the validity of conclusions based on such research.

Adolescents exhibit seemingly unlimited variation, as past studies have clearly demonstrated. The fact that significantly consistent relationships do exist in the presence of such variation in growth patterns is one reason for expecting close correlation between these factors when considered on an individual basis.[5,7,2,19,24,27,35-37]

System of Skeletal Maturation Assessment (SMA)

The methodology for this study is to examine groups as a whole in relation to specific individual maturational characteristics. The system of evaluating hand-wrist radiographs presented here has been in progressive development for more than four years. It has been found to be generally valid in both clinical and research situations.

The system uses only four stages of bone maturation, all found at six anatomical sites located on the thumb, third finger, fifth finger and radius, as seen in Fig. 1. Eleven discrete adolescent skeletal maturational indicators (SMI's), covering the entire period of adolescent development, are found on these six sites.

The sequence of the four ossification stages progresses through epiphyseal widening on selected phalanges, the ossification of the adductor sesamoid of the thumb, the 'capping' of selected epiphyses over their diaphyses, and the fusion of selected epiphyses and diaphyses (Fig. 2). The sequence of occurrence of the eleven indicators is exceptionally stable. Only three deviations have been detected in over two thousand observations, and these did not affect any interpretations.
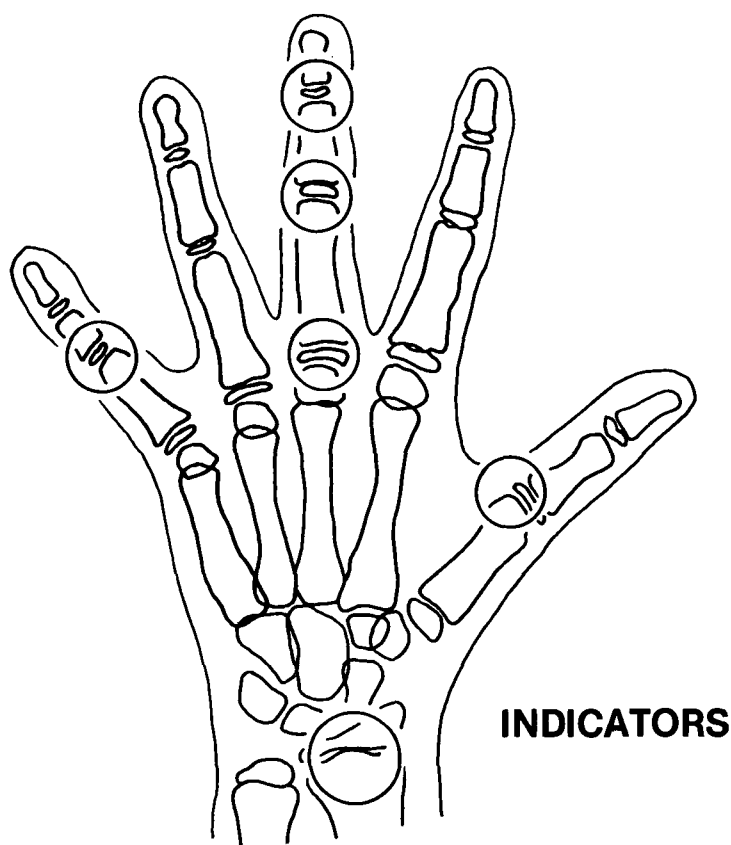
INDICATORS

Fig. 1   Sites of skeletal maturity indicators.

Widening of the epiphysis relative to its diaphysis is a progressive process. The epiphysis first appears as a small center of ossification centrally located in the diaphysis. When it has developed laterally to the width of the diaphysis, it is considered applicable as an SMI in this system.

Capping occurs in the transition between initial widening and fusion of the epiphysis and diaphysis. It is the stage in which the rounded lateral margins of the epiphysis begin to flatten and point toward the diaphysis, with an acute angle on the side facing the diaphysis. The time of first appearance of this capping is applicable as an SMI.

Fusion between the epiphysis and diaphysis follows capping. It also begins centrally and progresses laterally, until the two formerly separate bones become one. The time of completion of this fusion, with a smooth continuity of the surface at the junction area, is applicable as an SMI. Bony lines that may remain visible even years after completion of the fusion process are not relevant.

Ossification of the adductor sesamoid of the thumb first appears as a small, relatively round center of ossi-
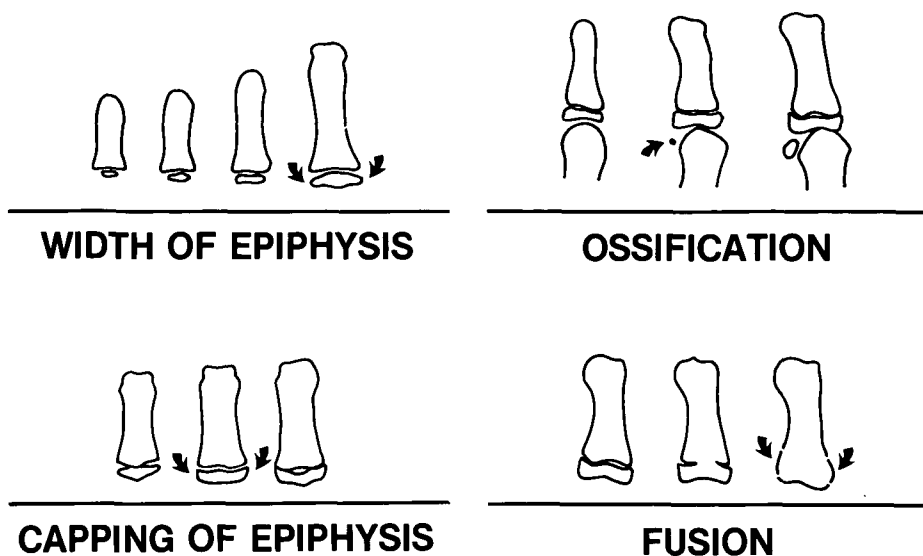
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WIDTH OF EPIPHYSIS

OSSIFICATION

CAPPING OF EPIPHYSIS

FUSION

Fig. 2 Radiographic identification of skeletal maturity indicators.
A. Epiphysis equal in width to diaphysis.
B. Appearance of adductor sesamoid of the thumb.
C. Capping of epiphysis.
D. Fusion of epiphysis.

fication medial to the junction of the epiphysis and diaphysis of the proximal phalanx. It then becomes progressively larger and more dense. It is the first observation of the existence of this bone that is considered applicable as an SMI. This occurs after the SMI's based on epiphyseal widening, but before those based on capping.

The individual maturity indicators are illustrated in Fig. 3 and listed below in chronological order.

Skeletal Maturity Indicators (SMI)

Width of 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

One soon becomes familiar with the nature and sequence of appearance of the maturity indicators, and inspection and rating of a hand-wrist radiograph requires little time.

A systematic observational scheme such as that shown in Fig. 4 can further facilitate SMI evaluation. With this approach key stages are checked first, rather than looking for maturity indicators in numerical order, leading
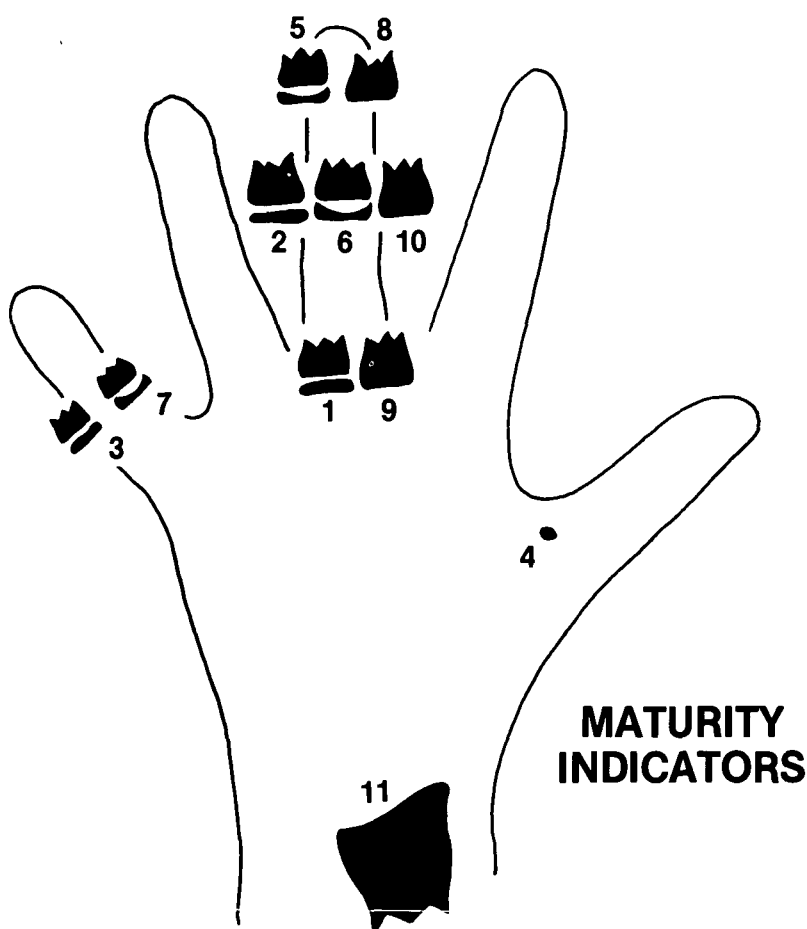
Fig. 3   Eleven skeletal maturity indicators (SMIs).

to rapid identification of the applicable SMI.

A useful first step is to determine whether or not the adductor sesamoid of the thumb can be seen. If not, then the applicable SMI will be one of those associated with early epiphyseal widening rather than capping. If the sesamoid is visible, then either the sesamoid or an SMI based on capping or fusion will be applicable.

DEVELOPMENT OF THE SYSTEM OF SKELETAL MATURATION ASSESSMENT (SMA)

METHODS AND MATERIALS

Both longitudinal and cross-sectional sample groups were evaluated in this study. Longitudinal data is essential for deriving information on absolute growth and growth velocities over specific time periods. Cross-sectional samples are useful in reducing

HAND-WRIST OBSERVATION SCHEME

4.
OSSIFICATION
ADDUCTOR SESAMOID
THUMB

NO?   YES?

WIDTH
1. PROX. PHALANX
THIRD FINGER

WIDTH
2. MIDDLE PHALANX
THIRD FINGER

WIDTH
3. MIDDLE PHALANX
FIFTH FINGER

FUSION
8. DISTAL PHALANX
THIRD FINGER
NO?   YES?

CAPPING
5. DISTAL PHALANX
THIRD FINGER

FUSION
9. PROX. PHALANX
THIRD FINGER

CAPPING
6. MIDDLE PHALANX
THIRD FINGER

FUSION
10. MIDDLE PHALANX
THIRD FINGER

CAPPING
7. MIDDLE PHALANX
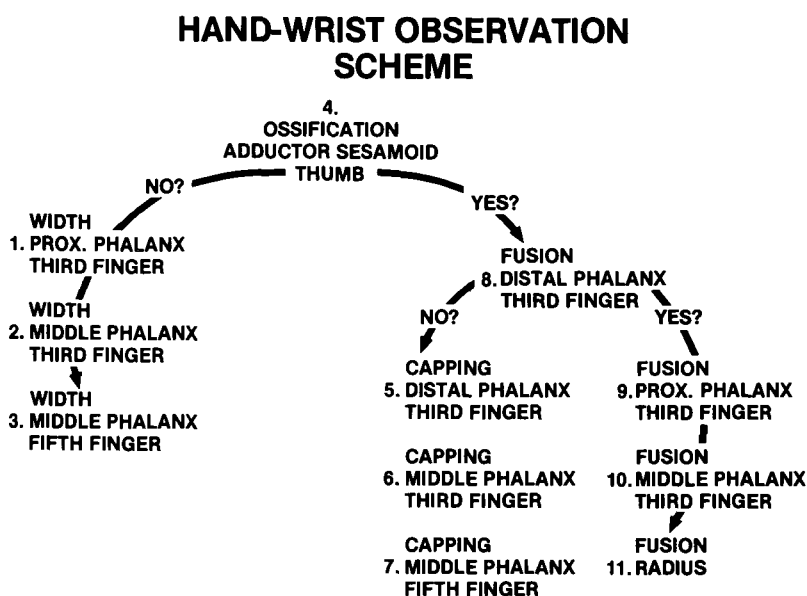**FIFTH FINGER**

FUSION
11. RADIUS

Fig. 4   An observational scheme for assessing SMIs on a hand-wrist radiograph.

secular error in the chronology of on-set and progression of growth during adolescence.[1,3-4,8]

Longitudinal sample

Longitudinal population data was derived from the Denver Child Re-search Council study that was active between the years 1927 and 1967. Physical measurements of 170 females and 164 males were recorded monthly up to three months of age, at three-month intervals up to six months of age and then semiannually until adulthood. Continuing records were made on most of those subjects be-yond 25 years of age. That data[40] on changes in statural height was used in this study.

Additional longitudinal records on a sampling of 36 females and 32 males from the above population were also used. The records were made avail-able for duplication through the cour-tesy of the Department of Orthodon-tics, University of Connecticut Health Center. That longitudinal series in-cluded anthropometric data, lateral and P-A cephalometric radiographs, and hand-wrist radiographs. The hand-wrist radiographs were not avail-able for each period, but were ade-quate in number for this investiga-tion.

The entire sample of lateral ce-phalometric and hand-wrist radio-graphs was copied on 35mm color film at a 1:8 reproduction ratio. A drawing table was adapted for rear projection to allow 8:1 projection from below the table top surface to provide a full-size image for evaluation.
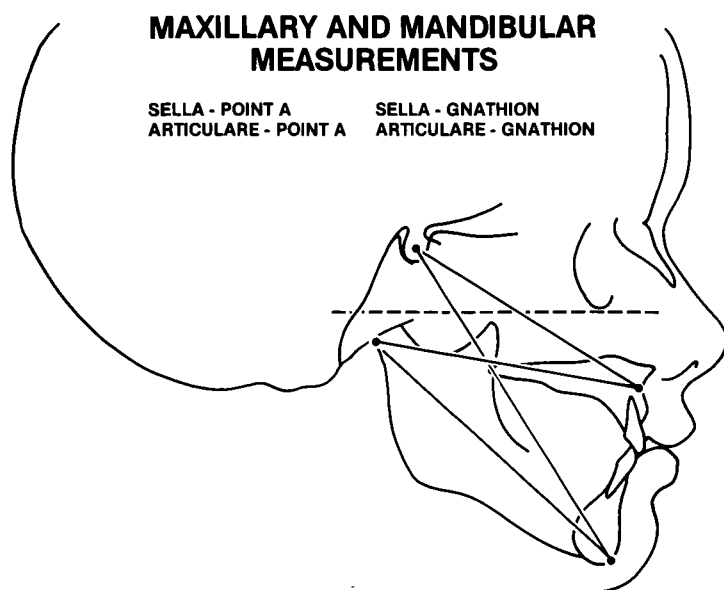
MAXILLARY AND MANDIBULAR MEASUREMENTS

SELLA - POINT A   **SELLA - GNATHION**
ARTICULARE - POINT A **ARTICULARE - GNATHION**

Fig. 5 Cephalometric measurements used to assess facial growth
in relation to SMIs.

Cross-sectional sample

The cross-sectional sample was obtained from treatment records of patients undergoing orthodontic treatment. More than 1400 hand-wrist radiographs of patients in the author's practice were surveyed, and 1040 selected for study. These were supplemented by 60 additional radiographs from the treatment files of the orthodontic department at the Eastman Dental Center, to provide a total sample of 1100 equally divided between males and females. The sample was then divided into female and male subsample groups corresponding to the eleven SMI's.

Measurement and evaluation

As seen on Fig. 5, two maxillary and two mandibular cephalometric measurements were selected to evaluate facial growth in relation to statural growth. Other studies utilizing these same measurements have found that significant relationships do exist between facial and statural changes.[19,24,27,29,41]

The maxillary measurements are sella-point A (S-A) and articulare-point A (Ar-A). The mandibular measurements are sella-gnathion (S-Gn) and articulare-gnathion (Ar-Gn).

Absolute values and incremental changes for statural height and the

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four facial planes were recorded and analyzed. Percentages of total growth completed were computed and analyzed at specific maturational levels.

Many formulas are available for calculating growth rates. The relative growth rate formula used here was selected for its applicability to demonstrating percentage changes in growth of the selected facial and statural height measurements.[7]

Relative growth rate provides an accurate index of acceleration and deceleration of growth over specific time periods. This requires the chronologic age of the individual and the measurement values (M) recorded at each record date.

$$\text{Relative growth rate} = \frac{M_2 - M_1}{M_{average}} \times \frac{100}{\text{length of period}}$$

By including elapsed time in the formula, growth changes that occurred over varying periods of time are all converted to annual rates, so growth rates can be compared. This method also allows easier comparison of an individual's growth pattern to group data. Conversion to percentage measurements of growth change by this method tends to minimize abrupt changes that may occur because of therapy or other reasons.

Separate data for the female and male longitudinal population groups was evaluated from birth to adulthood. This enabled a consideration of the general nature of the longitudinal changes, comparisons between the sex groups and development of a population standard so that the validity of the smaller longitudinal sample could be established.

It was concluded that the female and male longitudinal sample groups are valid representations of the total longitudinal population group.

In order to establish average age standards for the eleven SMI's, means and standard deviations were computed for both the longitudinal and cross-sectional female and male groups. Table 1 shows these values for each skeletal maturational age. Note the earlier age of maturational development for the female group.

TABLE 1

Chronologic Age Values for Adolescent Skeletal Maturity Indicators

SMI No.	Female		Male		
	Mean	S.D.	Mean	S.D.	Diff.
1	9.94	.96	11.01	1.22	1.07
2	10.58	.88	11.68	1.06	1.09
3	10.88	.99	12.12	1.00	1.23
4	11.22	1.11	12.33	1.09	1.11
5	11.64	.90	12.98	1.12	1.35
6	12.06	.96	13.75	1.06	1.69
7	12.34	.90	14.38	1.08	2.04
8	13.10	.87	15.11	1.03	2.01
9	13.90	.99	15.50	1.07	1.61
10	14.77	.96	16.40	1.00	1.62
11	16.07	1.25	17.37	1.26	1.30

The sex difference in time was approximately one year at maturity levels 1 and 2, increased to two years at SMI levels 7 and 8, and then decreased to approximately 1.3 years at SMI level 11.

The relative chronologic age distributions for the female and male Skeletal Maturity Indicators are plotted in Fig. 6. This shows graphically that the ages of occurrence of the skeletal maturity indicators follow a gradual chronologic progression through the adolescent growth period.

The secular factor could be evaluated by comparing the female and male longitudinal and cross-sectional groups to establish similarities and differences in the age of occurrence of the SMI's.
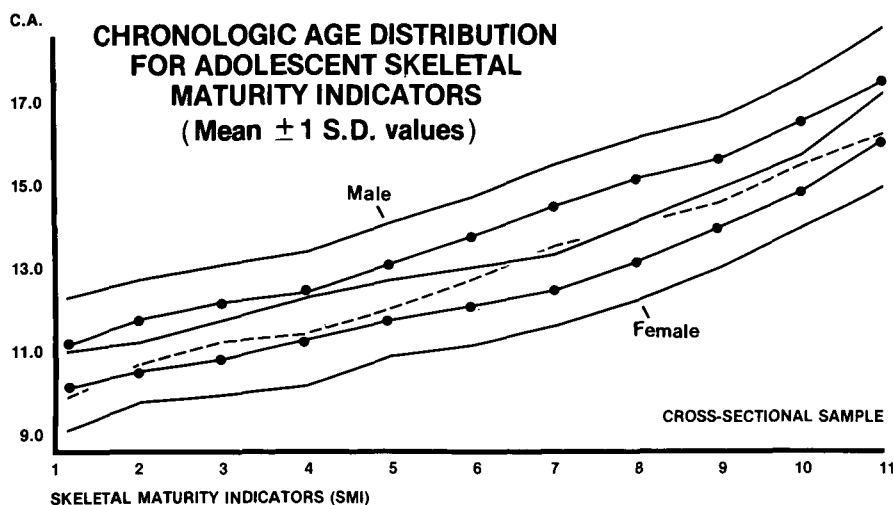
Fig. 6 Chronologic age distribution of appearance of SMIs.

The female groups demonstrated a close association between the ages of occurrence for the Skeletal Maturity Indicators, as seen in Fig. 7. The cross-sectional sample demonstrated a slightly later SMI occurrence up to level 6, after which the longitudinal female group showed the latest ages of SMI occurrence. The differences between mean values was statistically significant at the .05 level only at SMI's 2 and 8.

The male longitudinal and cross-sectional groups demonstrated a lesser degree of association in the timing of the maturity indicators, as seen in Fig. 8. The longitudinal sample showed a later age of occurrence than the cross-sectional sample through the entire growth period. This was most noticeable in the first part of the growth period, but significant statistical differences were found between the two sample groups at most maturity levels.

Comparisons were also made between the ages of appearance of the SMIs for the female and male chronologic longitudinal and cross-sectional

groups, with significant statistical differences found at all maturity levels.

To determine whether maturational age is a more valid and reliable means of sample groupings than chronological age, data related to longitudinal statural height and the four facial measurements was organized both chronologically and maturationally. Standard deviations from the mean values were calculated for statural height and the four maxillary and mandibular cephalometric measurements at each level.

A definite pattern of broader distribution of the chronologically based values was found. The findings support the general conclusion that organization of the data on a maturational basis provides a more homogeneous grouping than grouping chronologically.

The cross-sectional values for the chronologic age distributions of the female and,, male SMIs provide the basis for the charts of adolescent maturation level in Figs. 9 and 10. These can be used for plotting individual

COMPARISON OF LONGITUDINAL
AND CROSS-SECTIONAL SAMPLES
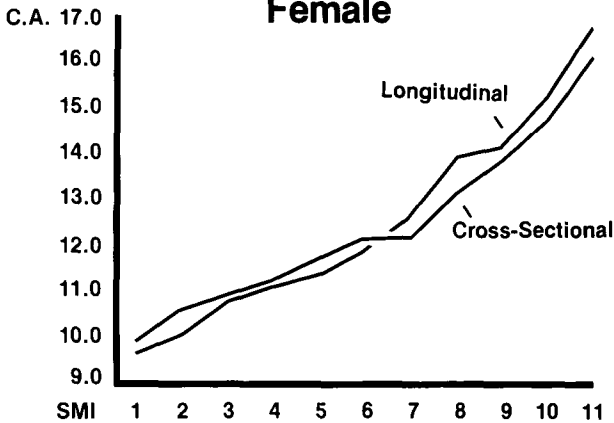### Skeletal Maturity Indicators
Female

Fig. 7 Comparison of average age of appearance of SMIs in longitudinal and cross-sectional female samples.

COMPARISON OF LONGITUDINAL
AND CROSS-SECTIONAL SAMPLES
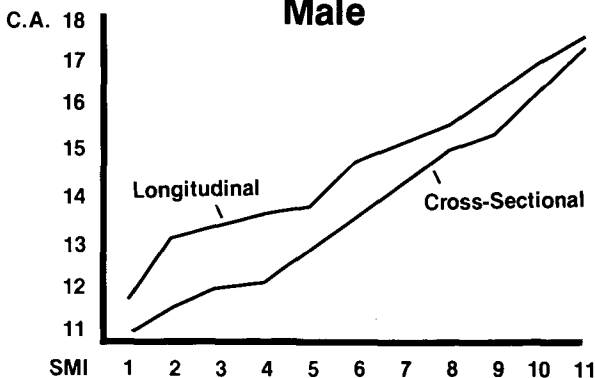### Skeletal Maturity Indicators
Male

Fig. 8 Comparison of average age of appearance of SMIs in longitudinal and cross-sectional male samples.
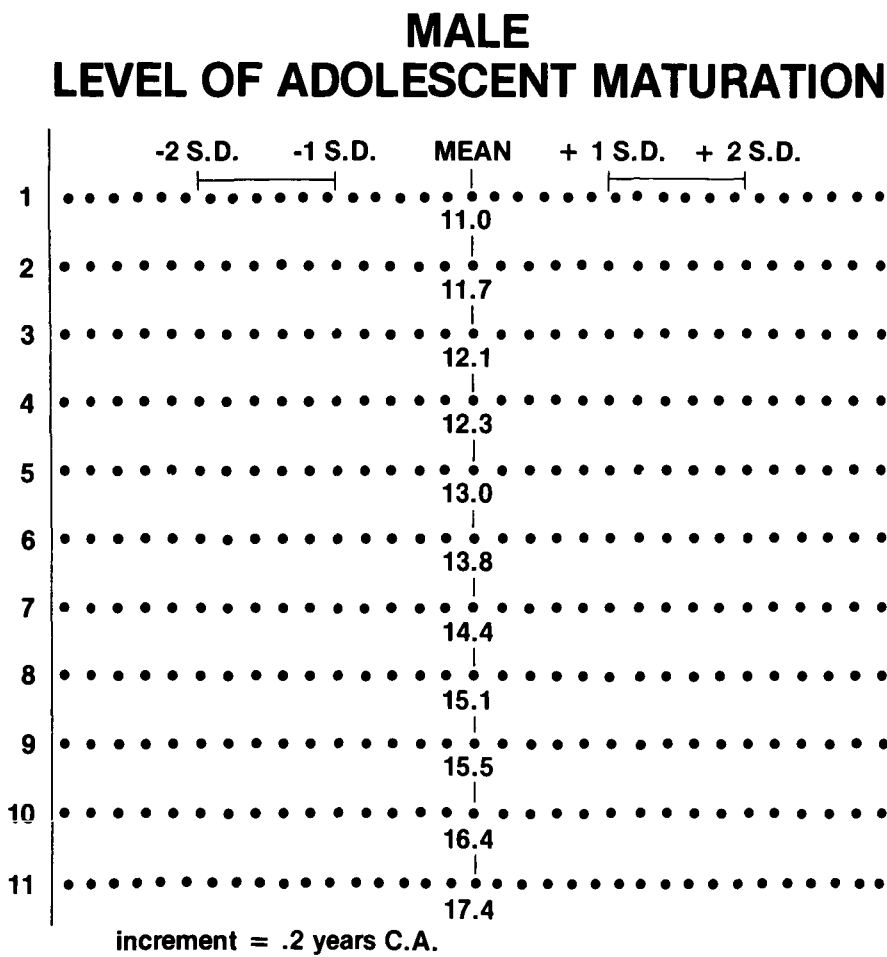
MALE
LEVEL OF ADOLESCENT MATURATION

	-2 S.D.	-1 S.D.	MEAN	+ 1 S.D.	+ 2 S.D.

1 •
11.0

2 •
11.7

3 •
12.1

4 •
12.3

5 •
13.0

6 •
13.8

7 •
14.4

8 •
15.1

9 •
15.5

10 •
16.4

11 •
17.4

increment = .2 years C.A.

Fig. 9   Chart for plotting level of maturation for males.

FEMALE
LEVEL OF ADOLESCENT MATURATION

| | -2 S.D. | -1 S.D. | MEAN | + 1 S.D. | + 2 S.D. |

increment = .2 years C.A.

1 9.9
2 10.6
3 10.9
4 11.2
5 11.6
6 12.0
7 12.3
8 13.1
9 13.9
10 14.8
11 16.1
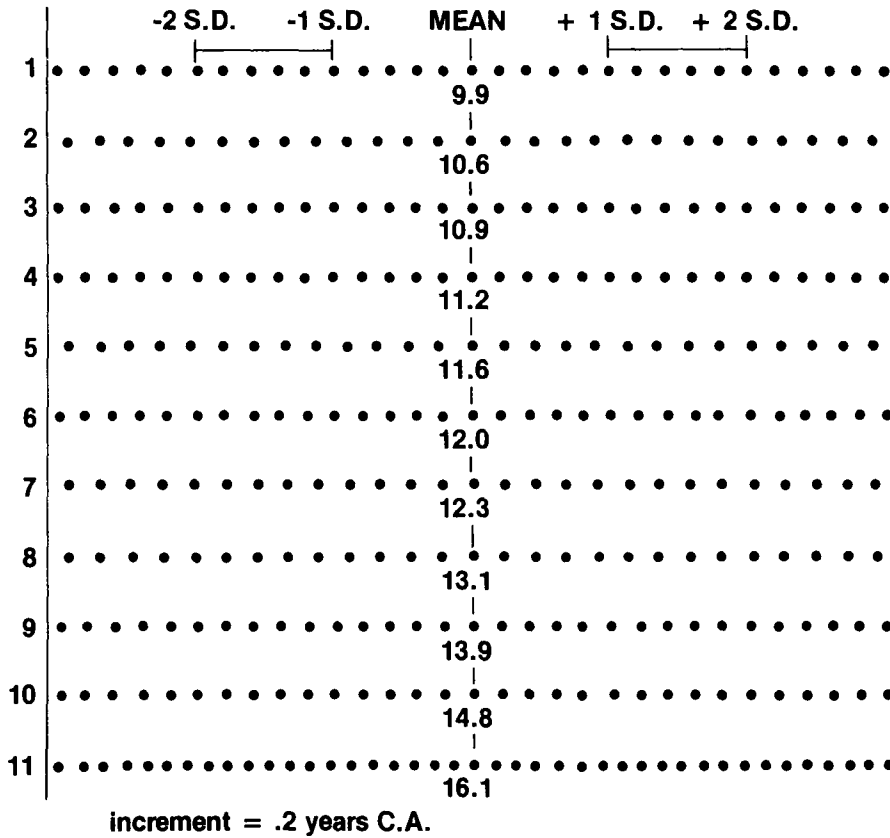
Fig. 10 Chart for plotting level of maturation for females.
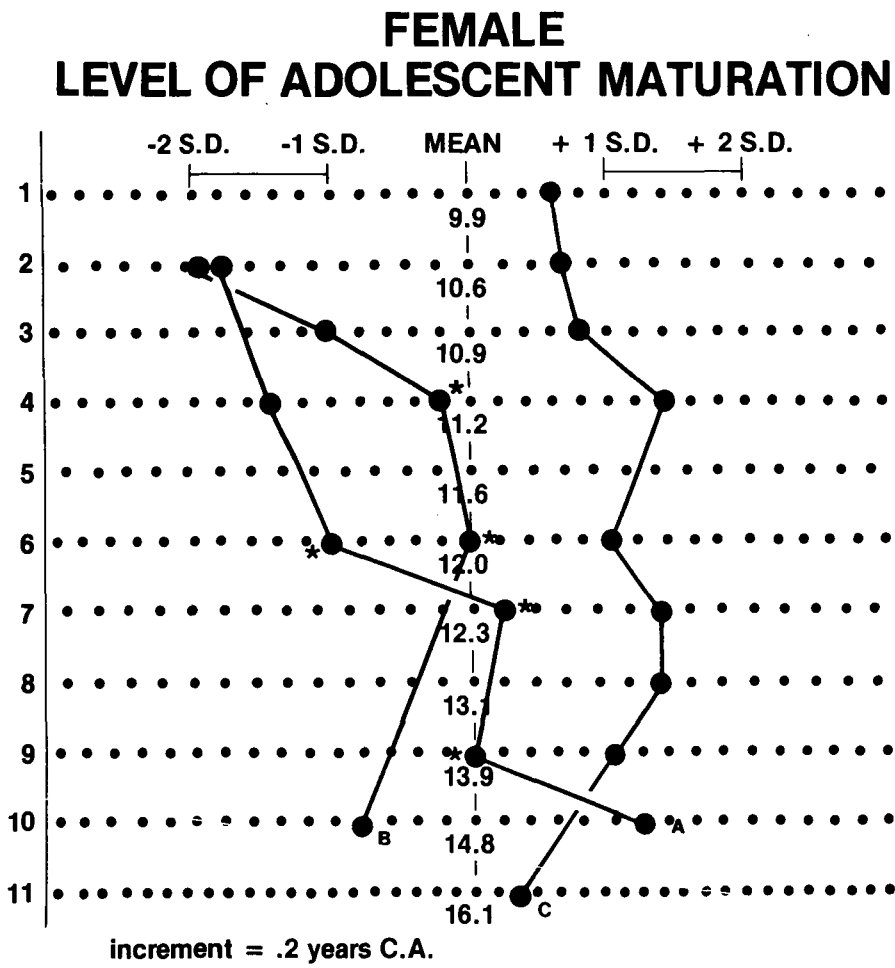
FEMALE
LEVEL OF ADOLESCENT MATURATION

Fig. 11   Changing maturational levels for three girls.

% Increment
per year
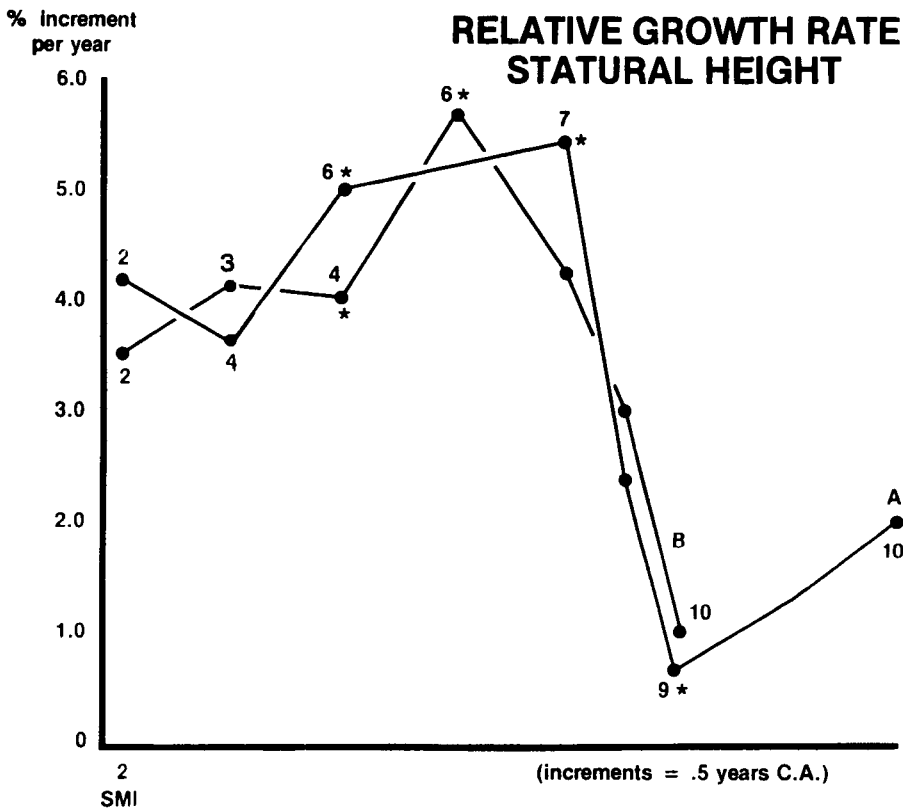
**RELATIVE GROWTH RATE
STATURAL HEIGHT**

Fig. 12 Growth rate in statural height for two girls.

age values for each level of skeletal maturation to show relative maturational level at specific SMI levels.

Fig. 11 shows the changing maturational levels for three girls. The adolescent growth period for A and B began about two standard deviations later than the mean values, while it was close to the mean value for C.

Although A and B were both equally below the average in the initiation of their adolescent growth at SMI level 2, their maturational patterns differed considerably in the later stages. At SMI level 6, A showed an abrupt acceleration in maturational development, leading to a somewhat advanced level of maturation at SMI level 10. On the other hand, the earlier acceleration of B brought her up to the average at SMI level 4, but a later deceleration after SMI level 6 resulted in a delayed attainment of level 10.

Girl C showed. average or slightly accelerated maturational levels through the entire adolescent growth period, with some deceleration at SMI level 9. No abrupt changes were noted at any level of maturation.

Fig. 12 shows relative growth rate in stature for A and B, with the SMI levels shown. When the relative growth rate curves are both oriented at the earliest SMI level and then
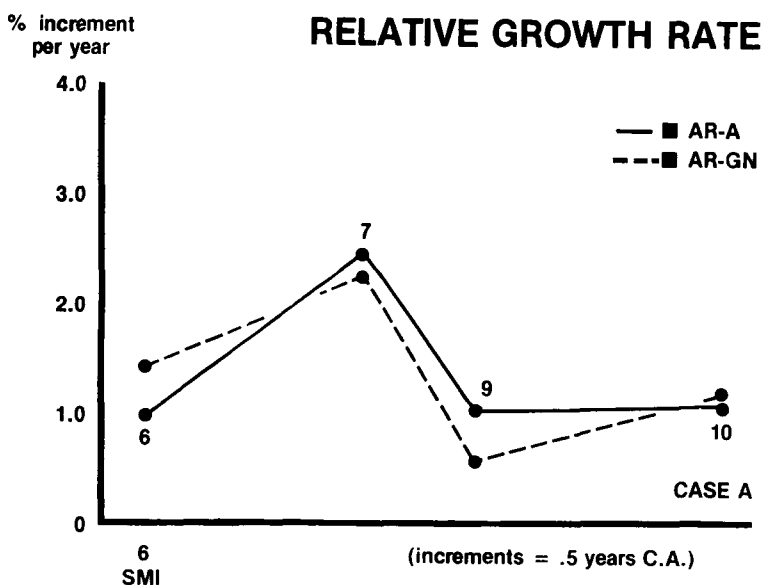
RELATIVE GROWTH RATE

Fig. 13   Growth rates for maxilla and mandible in one case.

judged chronologically, the velocity of growth changes can be directly compared. This type of orientation also allows comparison of the relative chronologic ages of SMI occurrence for the two individuals.

Specific differences in maturational development are directly related to alterations in growth velocity. Girl A demonstrated an acceleration in incremental changes expressed as percent per year at SMI 6, followed by a deceleration at SMI 7 and a resurgent acceleration at SMI 9.

Girl B also showed a good correlation between maturational development and growth velocity. This can be seen by comparing the leveling off between SMI 4 and 6 after a period of accelerated growth, followed by marked deceleration between SMI 6 and 10.

Variations were found in the time intervals between SMI's for both A

and B. Girl A required a significantly longer time period to reach level 10, even though she was ahead of B during the early part of the adolescent growth period. It appears that patterns of growth acceleration and deceleration are directly associated with the time schedule of maturational development.

Fig. 13 shows the relationship between facial growth and skeletal maturation for patient A. Ar-A and Ar-Gn demonstrated close correlation between relative growth rate patterns and level of maturation patterns, with a striking similarity between maxillary and mandibular growth patterns. For both the maxillary and mandibular measurements an acceleration in growth velocity occurred between skeletal maturation levels SMI 6 and 7, followed by a deceleration until level 9, where the velocity levelled off or increased slightly.
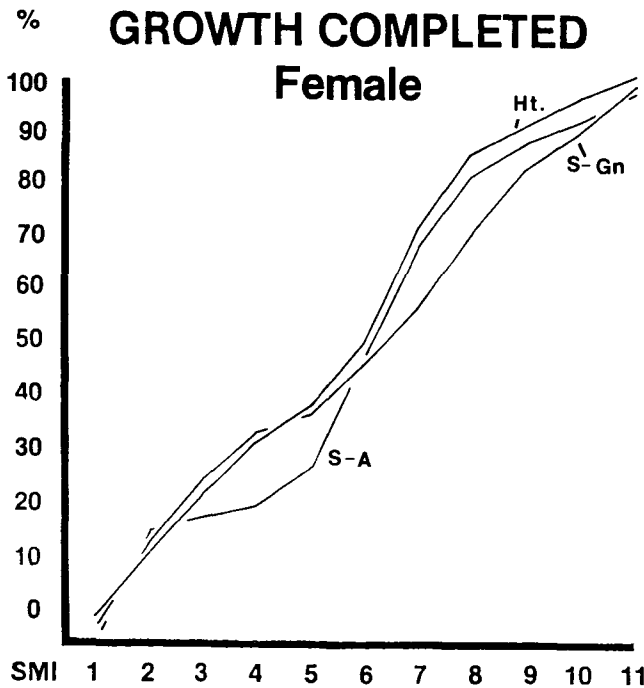
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Fig. 14   Percentage of adolescent growth completed, female average.

Percentage of growth completed

The percentage of adolescent growth completed is an especially useful value in the study of maturational changes. This computation provides a basis for making clinical interpretations of the amount of skeletal growth that has already occurred and for predicting future growth.

As seen in Fig. 14 and Table 2, both mandible and statural height in females showed very similar percentages of adolescent growth completed

TABLE 2

Percent of Total Adolescent Growth Completed

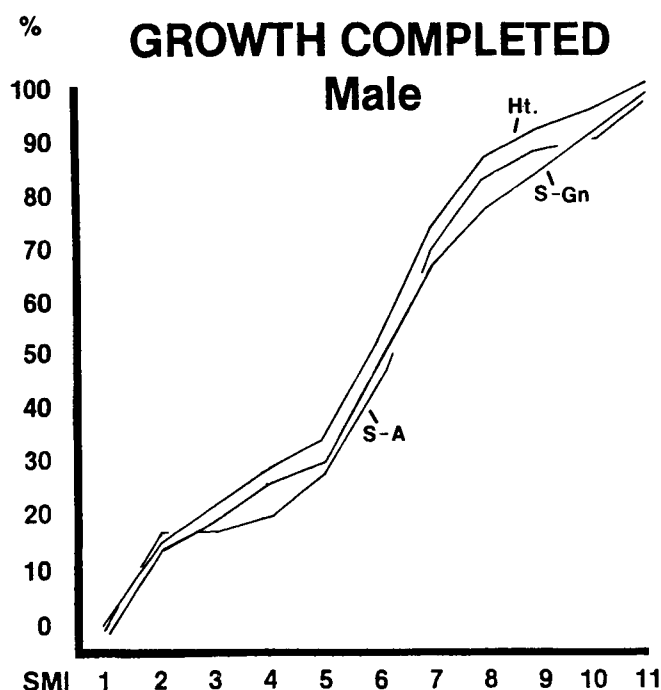|	Female		
SMI	Height	S-A	S-Gn
2	12.2	16.7	14.7
3	22.5	18.5	25.0
4	32.7	20.3	33.1
5	39.8	28.6	38.3
6	51.7	49.7	47.0
7	73.6	69.0	58.0
8	86.6	83.0	72.7
9	91.9	89.6	84.0
10	96.1	92.7	90.0
11	100.0	100.0	100.0

% GROWTH COMPLETED
Male

Fig. 15   Percentage of adolescent growth completed, male average.

TABLE 3

Percent of Total Adolescent Growth
Completed

SMI	Male Height	S-A	S-Gn
2	15.0	16.7	15.9
3	21.6	18.5	19.5
4	28.9	20.3	26.7
5	34.0	28.6	30.8
6	52.6	49.7	48.5
7	74.3	69.0	66.7
8	87.3	83.0	77.7
9	92.0	89.6	84.6
10	95.3	92.7	91.5
11	100.0	100.0	100.0

until approximately the time of peak growth velocity. At SMI level 6, the values representing height, maxilla and mandible all showed achievement of approximately 50% of adolescent growth. As growth velocity decreased during the later part of adolescence, the maxilla and mandible tended to lag behind skeletal growth.

Comparable values for males (Fig. 15 and Table 3) show similar patterns.

Female and male values are compared directly in Fig. 16 and Table 4.

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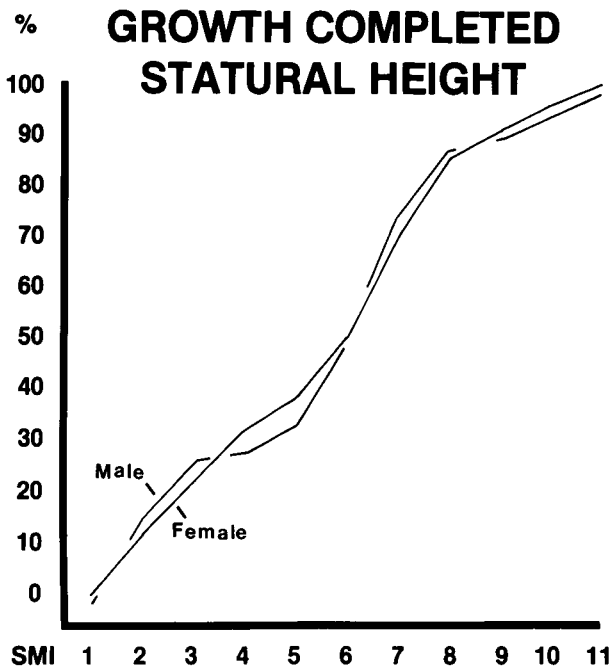
% GROWTH COMPLETED STATURAL HEIGHT

Fig. 16   Percentage of adolescent statural growth completed.

It is quite evident that both sexes completed similar percentages of total growth at comparable SMI's, even though it took place at quite different age periods.

Fig. 17 and Table 5 show the relative growth rates for female statural height, S-A and S-Gn. With the exception of SMI level 7, the percentage of incremental growth values for statural height exceeded the facial values at every maturational level up to 9. Considerably more growth intensity was seen in the period prior

TABLE 4

Percentage of Adolescent Statural Growth Completed

Female	SMI	Male
0.00	1	0.00
12.15	2	15.02
22.54	3	21.60
32.73	4	28.92
39.75	5	34.00
51.70	6	52.62
73.58	7	74.29
86.58	8	87.32
91.87	9	91.98
96.14	10	95.34
100.00	11	100.00

RELATIVE GROWTH RATE
Female
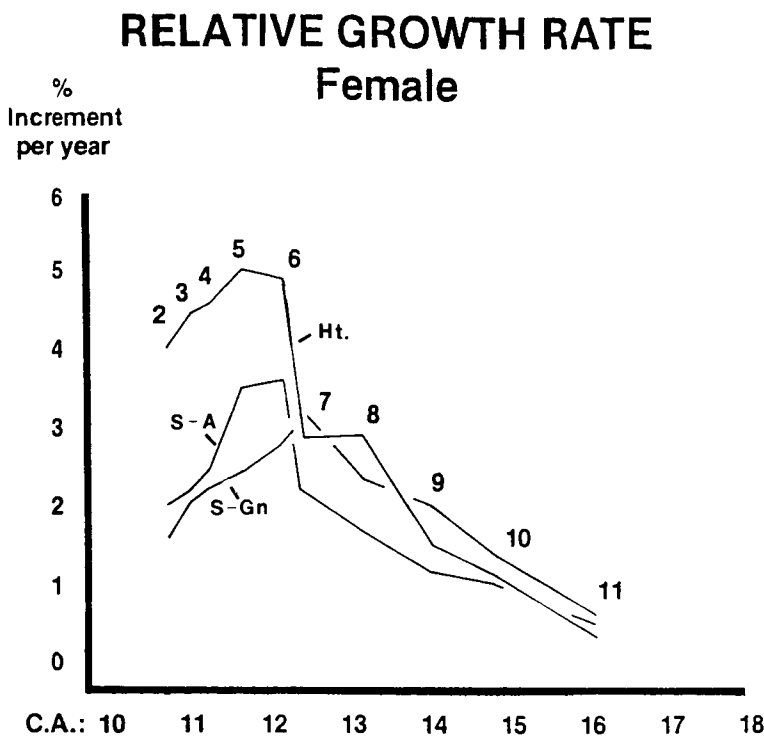
Fig. 17   Average female growth rate from SMI 2 to 11.

TABLE 5

Relative Growth Rate

SMI	Female Height	S-A	S-Gn
2	4.0	2.0	1.7
3	4.4	2.2	2.0
4	4.6	2.4	2.2
5	5.0	3.4	2.4
6	4.9	3.6	2.8
7	2.9	2.2	3.1
8	2.9	1.7	2.3
9	1.5	1.2	2.0
10	1.2	1.0	1.3
11	.3	.4	.5

to the time of maximum growth velocity than after for both statural height and facial values.

During the balance of the adolescent growth period, the mandibular growth velocity exceeded those of both statural height and the maxilla.

Fig. 18 and Table 6 show relative growth rates for the male sample. The growth rate for statural height again greatly exceeded those of maxilla and mandible up to SMI level 9, but the maximum growth velocity for statural height occurred at SMI level 6, one
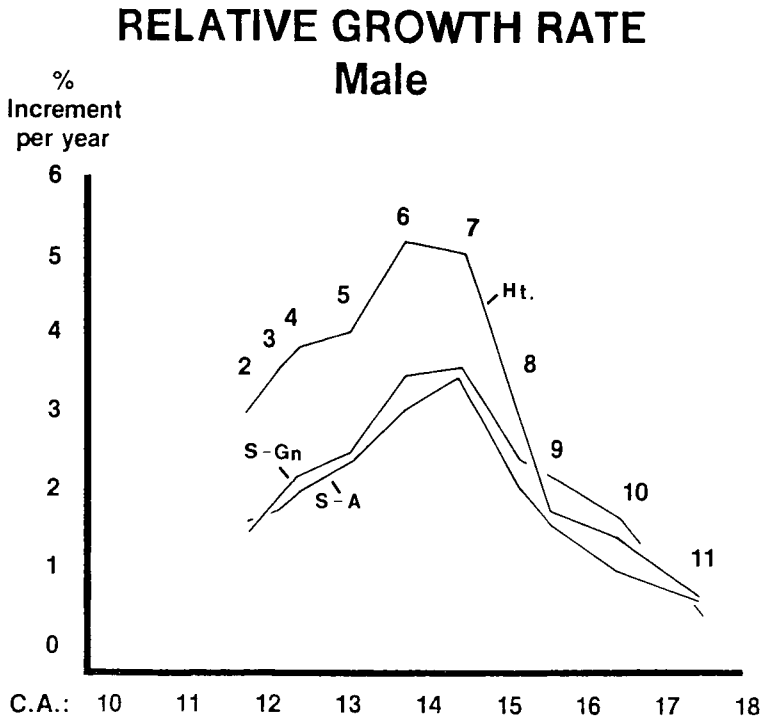
RELATIVE GROWTH RATE
Male

Fig. 18   Average male growth rate from SMI 2 to 11.

level later than in the female group.

Mandible and maxilla reached maximum growth rate at SMI level 7, also one level later than the female group.

The males also expressed a high growth velocity during the period prior to reaching peak velocity, followed by a rapid deceleration during the final adolescent growth period.

Growth rates in height for the male and female groups are compared in Fig. 19 and Table 7. Female growth rates were higher before the peak,

TABLE 6

Relative Growth Rate

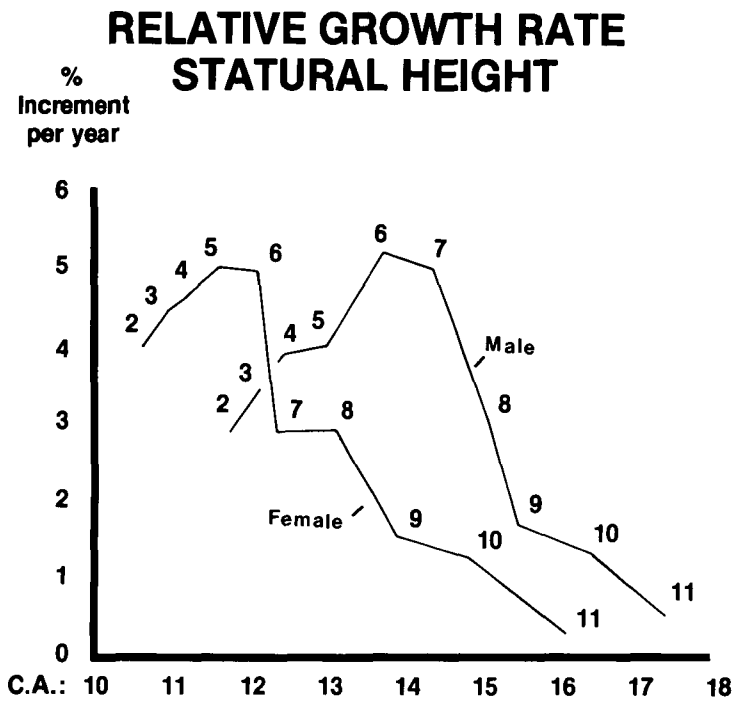| SMI | Male | | |
	Height	S-A	S-Gn
2	2.9	1.5	1.5
3	3.5	1.7	1.8
4	3.8	1.9	2.1
5	4.0	2.3	2.4
6	5.2	3.0	3.4
7	5.0	3.4	3.5
8	3.0	2.0	2.3
9	1.7	1.6	2.1
10	1.3	.9	1.6
11	.5	.5	.4

RELATIVE GROWTH RATE
STATURAL HEIGHT

Fig. 19   Average statural growth rate for females and males from SMI 2 to 11.

TABLE 7

Relative Growth Rate Statural Height

Female	SMI	Male
4.03	2	2.86
4.39	3	3.48
4.56	4	3.80
5.25	5	4.00
4.95	6	5.24
4.89	7	5.01
2.94	8	3.00
1.50	9	1.72
1.19	10	1.29
.34	11	.46

Percentage Increment per Year

with a shorter peak period than the males, but the overall patterns were quite similar.

DISCUSSION

The identification of skeletal maturation levels provides a very useful means of identifying specific points along the progressive path of adolescent growth. It is analogous to mileage signs posted along a highway between two cities. This provides a new dimension for evaluating general and individual growth, including facial growth.

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Dental, maturational and chronologic ages are not necessarily interrelated on a simple one-to-one basis, but they are nevertheless related. For example, it is common for an orthodontist to see a patient who is tall in stature, advanced in age but with more retained deciduous teeth than normal for his age. A short child may be more advanced in skeletal maturation than a taller child because of a genetic pattern that predestines a shorter adult.

All of these variations make maturational age a more valid means of judging physiologic development than chronologic age, which can be a most misleading piece of information.

Cephalometrics provides orthodontists with a large and useful body of descriptive information, and the associated methodology can also be applied to the measurement of growth changes within the craniofacial complex. Detailed information on changes in magnitude and direction of growth is available from longitudinal studies.[40-43]

The information that has been missing up to now is a measurement of time in dimensions relevant to the problem, and this may be the most important of all. Growth magnitude, direction and timing are intimately dependent on each other. A vertically growing mandible will display a greater magnitude of vertical growth during a time of accelerated growth velocity.

Too often we have gone through very detailed cephalometric analyses to measure direction and magnitude of facial growth and then related those values only in a most general way, if at all, to the timing of female and male growth patterns. Average growth curves are so variable that they are irrelevant and often misleading for individual diagnosis.

There is no valid physiologic reason to expect everyone to demonstrate similar chronologic times of maximum rate or acceleration of growth. Every person matures on a very individual schedule, and it is here that the value of hand-wrist films becomes apparent.

Clinically, the effectiveness of dentofacial orthopedic therapy can be dependent on all of these factors, but neither chronological age nor the level of dental development demonstrate sufficient correlation with individual maturational development to provide an adequate basis for the timing of therapy.

Orthodontic treatment of most dentofacial problems will be affected by concurrent growth regardless of appliance mechanics. The therapeutic effects of growth-related appliance mechanisms, such as extraoral or functional appliances, are especially sensitive to individual growth patterns. Maturational information can also be very valuable in selecting and executing orthodontic retention procedures or facial surgery.

SUMMARY

This study presents some of the basic relationships associated with skeletal maturation during adolescence, with a technique of Skeletal Maturation Assessment (SMA) utilizing hand-wrist radiographs to facilitate the objective evaluation of maturational development. Emphasis is on the maturational evaluation of the individual.

These are further evaluated in individual and group interrelationships of skeletal changes in statural height, maxilla and mandible. The findings are summarized below.

1. A system of Skeletal Maturational Assessment (SMA) offers an organized and relatively simple approach to assessing the level of skeletal maturation during adolescence. Skeletal maturity indicators (SMI's) provide a key to identification of progressive maturation levels.

2. Evaluation and demonstration of growth patterns, including growth rates for statural height and face, were studied in female and male longitudinal groups. Chronologic relationships of the skeletal maturational age levels for girls and boys were evaluated in large cross-sectional female and male samples.

3. Chronologic age levels and significant ranges of chronologic values were determined for the female and male maturity indicators. These values demonstrated a significant difference between girls and boys in the age of onset and the progression of adolescent skeletal maturity. This sexual difference was greatest during and shortly after the time of maximum growth velocity.

4. The ages of occurrence for the Skeletal Maturity Indicators in the more currently dated cross-sectional samples demonstrated some significant differences from the archival longitudinal groups. The cross-sectional SMI standards were considered more applicable for current usage.

5. Skeletal maturational age, as measured with the system of Skeletal Maturation Assessment (SMA), provides a more valid basis than chronological age for grouping individuals.

6. Individuals demonstrate wide variation in their maturational development. An early pattern of average, delayed or accelerated maturation will not necessarily hold as the adolescent growth period progresses; abrupt changes are not unusual.

7. Alterations in maturational development are directly related to growth velocity. Accelerations and decelerations in the rate of growth are associated with concomitant alterations in the advancement of maturational development as seen in the hand-wrist film.

8. Alterations in growth rate are directly associated with accompanying changes in the time intervals between specific maturational levels. This becomes especially significant during periods of accentuated growth velocity.

9. Facial growth as measured in the maxilla and mandible also demonstrated a close direct association between variations in the rate of growth and in skeletal maturation.

10. Both the maxilla and the mandible achieved their maximum growth rate later than statural height. Statural height demonstrated a greater percentage of completed growth than the facial measurements in the middle and late periods of adolescent growth.

11. Very close similarities were found between maxillary and mandibular patterns of relative growth rate, but the maxilla showed more growth completed than the mandible until the final stage, when the mandible tended to catch up.

12. Females tended to achieve a higher percentage of their total statural growth than males during early adolescence. After the time of maximum growth velocity, both sexes showed similar percentages of growth completed.

13. Velocity of statural growth tended to exceed facial growth velocities during early adolescence, with the

highest velocities for both occurring before the peak.

14. The females showed greater growth velocities and earlier maturation in stature and in the maxilla, while the mandibular velocities were highest in the males. After the peak, the growth velocities diminished more rapidly in the females than in the males.

Conclusions

This study demonstrates that hand-wrist radiographs can provide information on growth and maturation status with clinically important applications in dentofacial orthopedic diagnosis and therapy. The system of Skeletal Maturation Assessment (SMA) presented here provides a progressive scale of maturation levels through a series of readily identified skeletal maturation indicators (SMI's) that can be applied directly in clinical diagnosis.

More information and study of skeletal maturation are certainly required to further increase our knowledge in this area. Clinical evaluation and treatment can be much better oriented to the unique physiologic characteristics of the individual if this maturational information is made a part of the diagnostic and therapeutic regimen.

References

1. Katchadourian, H.: The Biology of Adolescence. W. H. Freeman and Co., San Francisco, 1977.

2. Smith, D. W.: Growth and its Disorders. W. B. Saunders Co., Philadelphia, 1977.

3. Falkner, F. and Tanner, J. M.: Human Growth, Vols. 1-3. Phenum Press, New York, 1978.

4. Tanner, J. M.: Growth at Adolescence, 2nd. ed. Blackwell Scientific Publications, Oxford, 1973.

5. Pomerance, H. H.: Growth Standards in children. Harper and Row, Publishers, Inc., Hagerstown, 1979.

6. Publications: National Center for Health Statistics. U.S. Dept. of Health, Education, and Welfare, Rockville, MD.

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

8. Lowrey, G. H.: Growth and Development of Children, 6th. ed. Year Book Medical Publishers, Inc., Chicago, 1973.

9. Todd, T. W.: Atlas of Skeletal Maturation, Part 1, Hand, Kimpton, London, 1937.

10. Greulich, W. W. and Pyle, S. I.: Radiographic Atlas of Skeletal Development of Hand and Wrist, 2nd. ed. Stanford Univ. Press, Stanford, 1959.

11. Pyle, S. I., Waterhouse, A. M. and Greulich, W. W.: A Radiographic Standard of Reference for the Growing Hand and Wrist. Press of Case Western Reserve Univ., Chicago, 1971.

12. de Roo, T. and Schroder, H. J.: Pocket Atlas of Skeletal Age. William and Wilkins Co., Baltimore, 1977.

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

14. Buckler, J. M. H.: A Reference Manual of Growth and Development. Blackwell Scientific Publications, St. Louis, 1979.

15. Lusted, L. B. and Keats, T. E.: Atlas of Roentgenographic Measurement, 4th. ed. Year Book Medical Publishers, Chicago, 1978.

16. Skeletal Maturity of Children 6-11 years (series 11—no. 149): National Center for Health Statistics. U.S. Dept. of Health, Education and Welfare, Rockville, 1976.

17. Skeletal Maturity of Youths 12-17 years (series 11—no. 160): National Center for Health Statistics. U.S. Dept. of Health, Education and Welfare, Rockville, 1976.

18. Houston, W. J. B.: Relationships between skeletal maturity estimated from hand-wrist radiographs and the timing of the adolescent growth spurt. European Journal of Orthodontics, 2:81-93, 1980.

19. Fishman, L. S.: Chronological versus skeletal age, an evaluation of craniofacial growth. Angle Orthodontist, 49:181-189, 1979.

20. Bjork, A. and Helm, S.: Prediction of the age of maximum puperal growth in body height. Angle Orthodontist, 37:134-143, 1967.

21. Grave, K. C. and Brown, T.: Skeletal ossification and the adolescent growth spurt. American J. Orthodontics, 69:611-619, 1976.

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

23. Grave, J. C.: Timing of facial growth: a study of relations with stature and ossification in the hand around puberty.

24. Nanda, R. S.: The rates of growth of several facial components measured from serial chephalometric roentgenograms. American J. Orthodontics, 41:658-673, 1975.

25. Bambha, J. K.: Longitudinal cephalometric roentgenographic study of the face and cranium in relation to body height. J. American Dental Assoc., 63:776-799, 1961.

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

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

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

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

30. Tofani, M. I.: Mandibular growth at puberty. American J. Orthodontics, 62: 176-195, 1972.

31. Burstone, C. J.: Process of maturation and growth prediction. American J. Orthodontics, 49:907-919, 1963.

32. Rose, G. J.: A cross-sectional study of the relationship of facial areas with several body dimensions. Angle Orthodontist, 30: 6-13, 1960.

33. Meredith, H. V.: Childhood interrelations of anatomic growth rates. Growth, 26:23-29, 1962.

34. Smith, R. J.: Misuse of hand-wrist radiographs. American J. Orthodontics, 77:75-78, 1980.

35. Krogman, W. M.: The meaningful interpretation of growth and growth data by the clinician. American J. Orthodontics, 44:411-432, 1958.

36. Singer, J.: Physiologic timing of orthodontic treatment. Angle Orthodontist, 50: 322-333, 1980.

37. Bowden, B. D.: Epiphyseal changes in the hand/wrist area as indicators of adolescent stage. Australian Orthodontic J., 4: 87-104, 1976.

38. McCammon, R. W.: Human Growth and Development. Charles C Thomas, Publisher, Springfield, 1970.

39. Pike, J. B.: A serial investigation of facial and statural growth in 7 to 12 year old children. American J. Orthodontics, 50:469-470 (abstr.), 1964.

40. Coben, S. E.: The integration of facial skeletal variants. American J. Orthodontics, 41:407, 1955.

41. Fishman, L. S.: A longitudinal cephalometric study of the normal cranio-facial profile, utilizing a proportional analysis of skeletal, soft-tissue and dental structures. International Dental J., 19:351-379, 1969.

42. Riolo, M., Moyers, R. E., McMamara, J. A. and Hunter, W. S.: An Atlas of Cranio-facial Growth. Univ. of Michigan, 1974.

43. Broadbent, B. H., Sr., Broadbent, B. H., Jr., Golden, W. H.: Bolton Standards of Dentofacial Developmental Growth. C. V. Mosby Co., Saint Louis, 1975.