A METHOD OF ASSESSING SKELETAL MATURITY FROM RADIOGRAPHS

A REPORT FROM THE OXFORD CHILD HEALTH SURVEY*

BY ROY M. ACHESON

The Social Medicine Unit, University of Oxford

It has long been realized that skeletal development is divisible into two components, increase in size and increase in maturity. Although closely integrated in the healthy child, each follows its own individual pattern. Increase in size is relatively easy to assess; skeletal maturation, however, is not only elusive of measurement, but is also difficult to define. It is usually accepted as being the metamorphosis of the cartilaginous and membranous skeleton of the foetus to the fully ossified bones of the adult. It can be studied conveniently by X-ray.

THE LITERATURE

The hand (including the wrist) has received most attention in the literature, both because it is easy to radiograph, and because it includes a wide range of bones suitable for study. The work of Rotch (1908, 1909), Flory (1936), Todd (1937) and Greulich & Pyle (1950) suggests that this region offers a fair index of the maturity of the entire skeleton of the healthy child. The most popular method of assessing maturity, therefore, has been to base comparison on a series of films which are typical of the various age groups. Such pictorial standards have been published by Wilms (1902), Rotch (1909), Englebach & McMahon (1924), Siegert (1935), Flory (1936), Todd (1937), Vogt & Vickers (1938), Greulich & Pyle (1950) and Mackay (1952). However, this 'inspectional' method involves considerable subjective error. To eliminate the latter, efforts were made to assess maturity by measuring the size of the shadows of various bones on the radiograph (Baldwin, 1921; Lowell & Woodrow, 1922; Carter, 1926; Baldwin *et al.* 1928; Sawtell, 1929; Prescott, 1933; Cattell, 1934; West, 1936). Such techniques were little used outside the centres in which they were devised because they were slow, cumbersome and inaccurate. Nevertheless, they had the great advantage that they offered skeletal maturity its own yardstick (Shuttleworth, 1938).

A third method has been evolved which entails radiographing all the joints on one side of the body, and counting the number of centres which have ossified; and later the number of epiphyses which have fused (Sontag, Snell & Anderson, 1939; Sontag & Lipford, 1943; Lurie, Levy & Lurie, 1943). This system involves many radiographic films and is therefore expensive; it also ignores the structural changes which occur in the epiphyses between their first appearance and their fusion with the diaphyses.

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THE DISADVANTAGES OF THE INSPECTIONAL TECHNIQUE

Of those described, the inspectional technique alone is generally used. The *Atlas* of Todd (1937), and its revision by Greulich & Pyle (1950) are the standard works of reference. These offer an excellent method for rapid assessment of maturational status suitable for general clinical purposes, but they do not permit an accurate evaluation of any film for the following reasons:

(1) *A fixed pattern of first appearance and subsequent development of centres is presupposed.* A standard film is published for each age group and, if these are studied serially, it is found that the centres appear in a certain order, and their subsequent development proceeds in a fixed pattern. There is, however, a considerable amount of evidence to show that a wide range of normal variation exists in the pattern of ossification, and that this variation is genetically determined (Pryor, 1908, 1936, 1939; Buschke, 1934, 1935; Reynolds, 1943). What is more, there is reason to believe that certain illnesses alter the order of appearance of the bones (Todd, 1930, 1933; Francis, 1939; Buehl & Pyle, 1942). It follows that many instances occur when the film to be assessed shows a pattern of ossification which is radically different from that of the standard. Assessment in these cases necessarily introduces a subjective error.

(2) *There is too long a time interval between the standard films.* During the greater part of childhood the standard films are placed 6 months apart. This coarse grouping is essential to the method because it is only if there is a very sharp distinction between two successive standards that any attempt can be made to overcome the pattern differences described in § (1) above. If the time interval between the standards is reduced, for instance to 1 month, the film of a child whose pattern of ossification differed radically from that shown in the *Atlas* might bear an equal resemblance to several successive standard films. In this way the subjective error in assessment would be further increased.

There are two more objections to the Inspectional Technique:

(3) *The necessity for a set of standards for each sex.* It is a commonplace that the female matures more rapidly than the male. It follows that at any age the two sexes will have reached different maturational levels, and therefore will require separate sets of standards. In other words, the term 'skeletal age 30 months' calls to mind no radiographic picture, unless it is qualified by the sex to which it applies.

(4) *The use of time as a yardstick.* Skeletal maturation is a process as distinct in itself as that of growing bigger or growing heavier. Therefore, just as growth is measured in inches and pounds, maturation should have units of its own. To speak of the mean skeletal maturity status of a group of children aged $2\frac{1}{2}$ years as 'skeletal age 30 months' is no more reasonable than to speak of their mean weight as being 'ponderal age 30 months'. Just as every child has its individual pattern of weight increase so it has its individual pattern of maturation. Both of these correlate with time, but neither correlates so closely that it can be looked upon as 'happening in months and years', for that, in fact, is what the concept 'skeletal age' implies. This concept (or misconception) has been an important factor in impeding the progress of understanding of this field.

For these reasons an attempt has been made to devise a method of assessing maturity in which:

(1) Every round bone and epiphysis can make its own contribution to each assessment, and so evaluation of a film can be made regardless of the pattern in which ossification is occurring.

(2) Small increases of maturity are recorded.

(3) Maturation is given a yardstick of its own, the units being Oxford Maturity Units.

(4) The same standards are used for both sexes, so that a dirct comparison can be made between the unit status of any boy and girl.

THE PRINCIPLES OF THE OXFORD METHOD

Todd's greatest contribution to this field of study was a description of the exact shadow changes in a radiograph which indicated increasing skeletal maturity. He concentrated his attention on the growing ends of the long bones: 'successive changes in outline of shaft ends and in contour of epiphysial ossification centres' (1937). Greulich & Pyle (1950) have, by illustrating the denominators of maturity in the round bones of the carpus, added to Todd's work.

In the Oxford Survey it was decided that a unit should be awarded to a bone as each distinct shape change made itself manifest, and in this way the sum total of units scored by a bone at any stage in its development would be an exact measure of its maturity. This technique is equally applicable to any part of the body, provided that the maturity denominators of the bones are clearly recognized. In the present paper the maturity indicators recognizable in the hand and knee of a healthy group of British children between the ages of 6 months and 5 years are described.* The indicators accepted in the hand and wrist are based upon those described by Greulich & Pyle (1950); they were chosen because they were easily recognized in a large number of films (see Fig. 1).

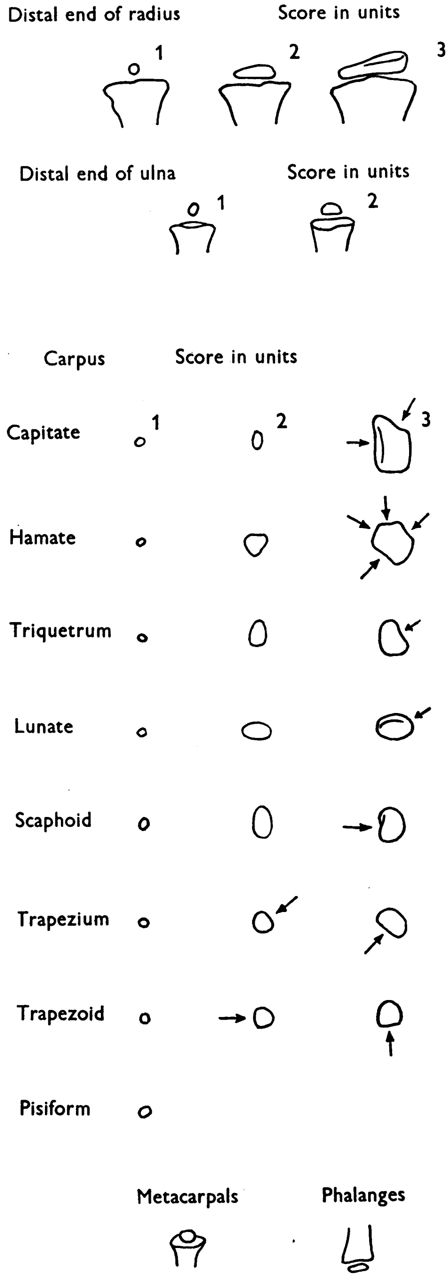

Fig. 1. For legend see p. 501 (after Greulich & Pyle).

* For details of recruiting and composition of the Oxford Child Health Survey see Ryle (1948) and Stewart & Russell (1952).

Fig. 1. Denominators of maturity—the hand (after Greulich & Pyle)

	Score in units		
	1	2	3
Distal end of radius	Primitive rounded centre	Broad laterally narrow medially	Volar margin of distal surface visible as a line
Distal end of ulna	Primitive rounded centre	Flat proximally rounded distally	
Carpus			
Capitate	Primitive rounded centre	Oval in appearance	Flattening in articulation with second metacarpal, and in articulation with the hamate
Hamate	Primitive rounded centre	Triangular shape	Evolution of surfaces articulating with triquetrum, metacarpals V and IV, and capitate
Triquetrum	Primitive rounded centre	Piriform shape	Surface articulating with lunate becomes distinct
Lunate	Primitive rounded centre	Oval shape	Volar surface of capitate articulation defined as a line
Scaphoid	Primitive centre (occasionally somewhat oval)	Definite ovoid	Surface articulating with capitate flattened
Trapezium	Primitive rounded centre	Slight flattening of surface articulating with first metacarpal	Slight flattening of surface articulating with scaphoid
Trapezoid	Primitive rounded centre	Slight flattening of surface articulating with capitate	Slight flattening of surface articulating with scaphoid
Pisiform	Primitive rounded centre	No further development noted in present series	
Metacarpals, Phalanges	Presence of epiphyses	Score. See text.	

The only previous work of reference known to the author for the knee is a pioneer monograph by Sick (1902), which deals with the subject very superficially. The suggested indicators shown in Fig. 2 have been selected because they were consistently observed in about 1200 serial antero-posterior films of this joint. Fig. 1 represents the bones of the left hand on a postero-anterior film and Fig. 2 the left knee on an antero-posterior film.

THE METHOD OF COMBINING THE INDIVIDUAL BONE SCORES TO INDICATE THE OVERALL MATURITY OF THE CHILD

The question of whether or not the maturational status of a child is accurately reflected by the sum total of the individual scores of all its bones raises some questions which, in the present state of knowledge, cannot be answered. In the first place, there is reason to believe that round bone, and epiphyseal ossification do not proceed at equal rates in all children. In other words, one healthy group may show relatively advanced development in the carpus and tarsus, whilst the ossification of their epiphyses is somewhat behind average. In another group the reverse may be true (Sawtell, 1929; Robinow, 1942; Buehl & Pyle, 1942; Schmid, 1949). It is therefore uncertain whether the maturity scores of these two types of bone are a measure of the same process. If there were two processes it might not be legitimate to add the round bone and epiphyseal scores together.

The next question that arises is whether the total scores for one anatomical area should be added to those from another. Do total hand points plus total knee points

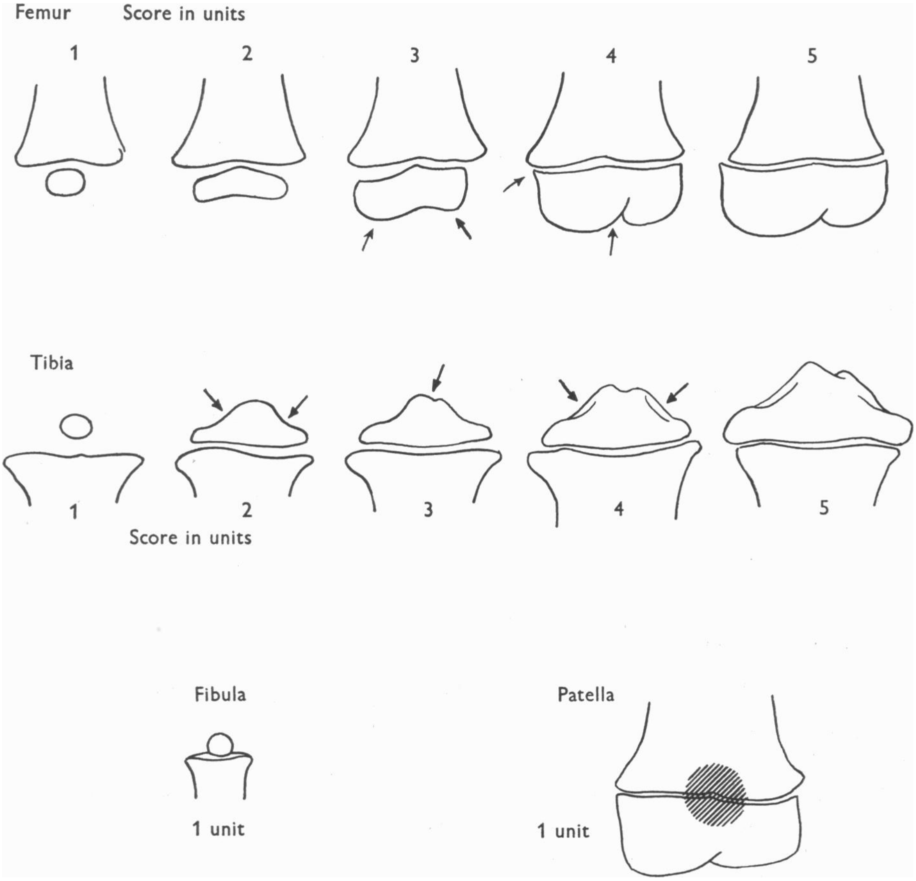

Fig. 2. Denominators of maturity—the knee

Femur

Score 1
Rudimentary centre usually rounded

Score 2
Epiphysis more elongated and somewhat 'banana shaped'

Score 3
Condyles visible as definite entities

Score 4
(*a*) line running from medial condyle into bone and/or (*b*) medial proximal corner of epiphysis becoming differentiated as a sharp point

Score 5
Epiphysis as broad as diaphysis (checked by measurement)

Tibia

Score 1
Rudimentary centre; usually rounded sometimes triangular

Score 2
Definite triangular shape with tendency to indentation on proximal surfaces

Score 3
Development of intracondylar eminence (attachment of ligaments). Higher on medial side

Score 4
Surface of tibial table begins to show itself as lines

Score 5
Epiphysis as wide as diaphysis (checked by measurement).

Score 1

Fibula Presence of epiphysis

Patella Seen as a denser shadow through lower part of femur give a more accurate picture of maturational status than considering one area alone? If there is a considerable difference between the scores of two regions, must this difference in itself be taken into account? That such differences exist has been shown (Sontag & Lipford, 1943; Mann, Driezen, Pyle *et al.* 1948), but these authors do not agree as to why they exist. In the face of these difficulties it is essential that arbitrary assumptions are made, with the reservation that these must be revised as knowledge of the subject advances. A pilot study of ninety-seven of the Oxford children (forty-five boys and fifty-two girls) was based on the following assumptions:

(1) That the hand and knee should be treated separately.

(2) That round bone and epiphyseal ossifications are facets of the same process, and that it is therefore justifiable to add their scores.

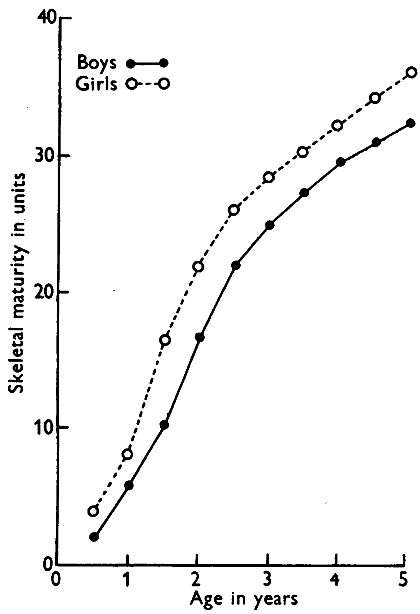

Fig. 3. The hand—gross maturity.

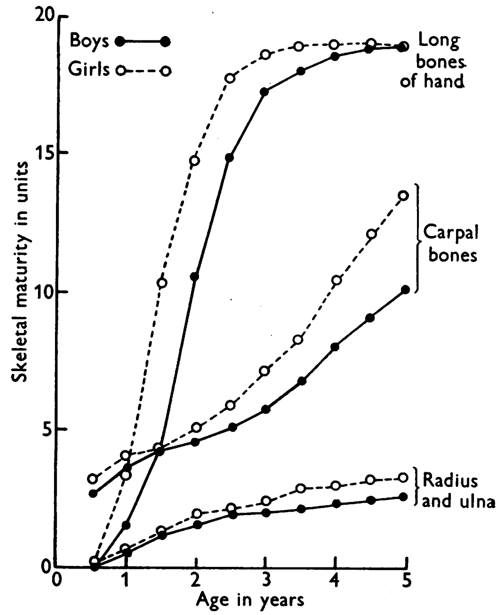

Fig. 4. The hand—maturity analysed.

(3) Should a rectilinear relationship not be found between skeletal maturation and age in respect of either region, that it is justifiable to contrive such a relationship. This assumption was made because the study of increments is greatly simplified if they are even throughout the period under observation.

It must be emphasized that these assumptions are recognized as being the basis of an experimental method of computation, and that each will be revised as and when advancing knowledge indicates that a revision is necessary.

The hand. Fig. 3 shows the mean score for the hand in Oxford Maturity Units, plotted against age. The lines are curved for both sexes. If the totals are broken down into their contributing parts: (i) the epiphyses of the long bones of the hand, (ii) the bones of the carpus, and (iii) the distal epiphyses of the radius and ulna, it becomes plain that the inequality of increment in each sex is due to the rapid appearance of the epiphyses of the long bones of the hand (Fig. 4). Equal increments (in keeping with assumption 2) can therefore be achieved either by awarding further points to these bones before the age of 5 years (thus making the curve steeper), or by scaling down their contribution to the total score. The first technique was attempted and abandoned because the only constant maturity indicator for these bones in every child during the age range under study, was the first appearance of the epiphysis. Therefore the contribution of these bones was scaled down. The distal and proximal phalanges of the thumb each scored full weight, i.e. one unit. Each

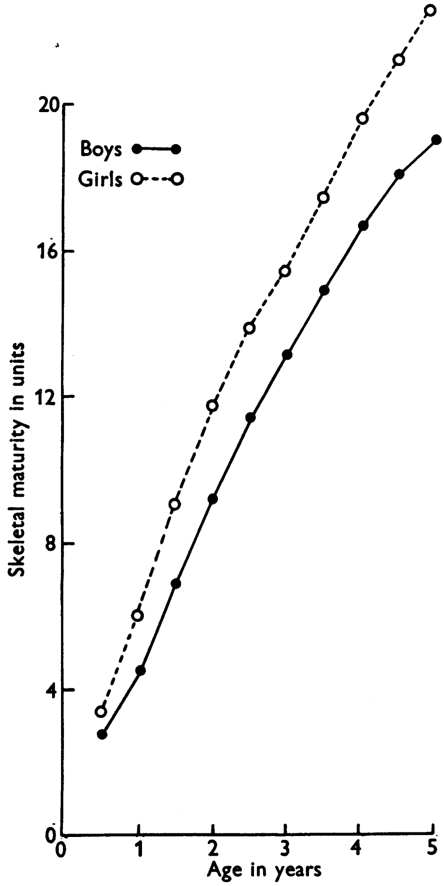

Fig. 5. The hand—corrected maturity.

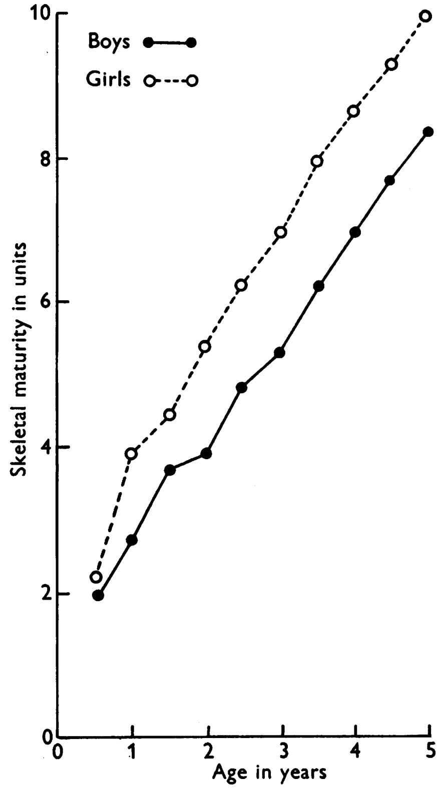

Fig. 6. The knee—maturity.

row of phalanges of the fingers scored one unit when they were complete, each epiphysis contributing 0·25 unit to the total score. The five metacarpals also contributed one unit between them, each being valued at 0·2 unit. In this way the overall contribution of the long bones of the hand was reduced from 18 to 6. The relationship of this corrected score with age is shown in Fig. 5 and Table 1. A reasonably straight line has been contrived.*

* The hand films have also been assessed against the standards of Todd (1937). This has been done so that the data are directly comparable with those of the American Growth Studies (Acheson & Hewitt, 1954).

The knee. No mathematical adjustment was necessary for this region. The mean scores (Table 2, Fig. 6) show that apart from irregularities during the early years the increments were fairly constant. These irregularities are due to the fact that some difficulty was experienced in defining satisfactory maturity indicators during this period.

DISCUSSION

It is now necessary to examine the efficiency of this technique. Sawtell (1929) stated that a measure which claims to assess skeletal maturity should correlate with height and with weight, and that it should demonstrate the precocity of the female. The present technique fulfils these three criteria. Flory (1936) wrote 'the critical test of a measure is the degree to which it predicts the characteristic to be measured rather than the degree to which it is related to other measures'. It is not yet possible to use the present technique to predict the time at which final maturity will be attained. However, this test must be applied as soon as the material for older subjects is available. It is acknowledged that sexual and skeletal maturity are very closely correlated (Abernethy, 1925; Richey, 1937; Shuttleworth, 1937, 1938; Buehl & Pyle, 1942, etc.) and so a further test will be the accuracy with which puberty can be predicted. At the moment its acceptance must depend on its compliance with the requirements of Sawtell (1929) and the fact that the maturation changes which it assesses are closely analogous to those described by acknowledged authorities (Todd, Greulich and Pyle).

Table 1. *Mean hand score in Oxford Maturity Units by age and sex*

Age (years)	Boys		Girls	
	Mean	S.D.	Mean	S.D.
½	2·7	0·9	3·3	1·2
1	4·4	1·1	5·9	1·5
1½	6·8	1·4	9·0	1·6
2	9·1	2·4	11·7	2·5
2½	11·3	2·1	13·8	2·1
3	13·1	2·2	15·4	2·7
3½	14·9	2·2	17·5	3·1
4	16·5	1·9	19·4	3·1
4½	17·8	1·9	21·0	3·4
5	19·0	2·0	22·8	3·2

Table 2. *Mean knee score in Oxford Maturity Units by age and sex*

Age (years)	Boys		Girls	
	Mean	S.D.	Mean	S.D.
½	2·0	0·1	2·2	0·7
1	2·7	0·3	3·9	0·6
1½	3·7	0·8	4·4	0·9
2	3·9	0·3	5·3	0·9
2½	4·8	0·6	6·2	1·2
3	5·2	0·8	6·9	1·4
3½	6·1	0·8	7·9	1·1
4	6·9	0·9	8·6	1·2
4½	7·6	0·9	9·2	0·9
5	8·3	0·9	9·9	1·2

When the technique has been worked out for the entire period of maturation it will probably be convenient to consider the maturational status of any bone or region in terms of percentages. For instance, the hand of a child may be described as being 34 % mature and its knee as 37 % mature. Not only would this enable a comparison to be made between the various parts of the body, but it is a statement which is easily intelligible because morphological maturity, the 100 % level, is inevitable in the healthy person (Krogman, 1949). In addition, the work of Bayley (1943*a*, *b*, 1946, 1952) suggests that such a statement may be of value in the prediction of final height.

SUMMARY AND CONCLUSIONS

Existing methods of assessing skeletal maturity are reviewed, and their shortcomings are discussed. A new method is suggested which is based on the recognition of maturity indicators described by acknowledged authorities. Details of the method are given for the hand and knee during the first 5 years of life; however, the technique may be applied to any part of the body throughout the developmental period. The necessity for considering skeletal maturity in units other than time is emphasized, and it is suggested that when the technique has been worked out for the entire developmental period it may be logical and convenient to express all skeletal maturity readings as percentages.

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