

## **An Automated Technique for the Radiographic Determination of Bone Age**

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**Abstract.** We have developed an automated procedure for determining bone-age in the monkey, *Macaca fascicularis*. The status of epiphysial junctions and sesamoids were determined from radiographs. Epiphyses were scored as either open or closed, and sesamoids were scored as either present or absent. Bone-age was calculated by a computer program that stored and used a data base of probabilities for epiphysial closure and sesamoid appearance. The simplicity of scoring, combined with the speed and accuracy of the calculations, make this technique potentially adaptable for use in a variety of primate species.

### **Introduction**

A number of excellent methods have been developed to estimate bone-age in human beings (1,3). These techniques are based on studies in large populations and require considerable training and experience to be used properly. Although some attempt has been made to extend these techniques to other primate species, the technical expertise and the large numbers of known-age animals required make this a difficult undertaking (2,4,6). Faced with this problem in the crab-eating monkey, *Macaca fascicularis*, we devised an automated approach. It can be used for animals that are old enough to have a combination of open and closed epiphyses, and has proven reliable, even in the hands of inexperienced personnel.

## Methods

**Analytical Technique.** A computer program is used for storage of normative data from age-known animals and for the automated, immediate calculation of bone-age in animals of unknown age. For each epiphyseal junction the probability of closure is tabulated as a function of age. To do this, radiographic data from age-known animals on the state (open or closed) of each epiphyseal junction is divided into age groups. Calculations involving the appearance of sesamoids are identical to those done for epiphyseal closure; for simplicity we will use the term epiphyseal closure to refer to both the closure of epiphyses and the appearance of sesamoids. An example of this procedure for three hypothetical junctions (A, B, and C) over a 24-month span is shown in Table I.

It should be noted that for each epiphysis, the probability of closure increases with age, within a certain age range, and that the age of closure is different for each epiphysis. The data in adjacent groups were pooled to compute the probability of each junction being closed at the median age of the two groups, as shown in Table II.

For example, there are 10 animals in the combined 9–12 and 12–15 month groups, and epiphysis A was closed in four of them. Therefore, the probability of A being closed at 12 months is estimated to be  $4/10 = 0.40$ .

Once this normative data base of probabilities has been collected, the information is then used to estimate bone-ages of animals with unknown birthdates. This procedure is best explained by another example. We assume that we have obtained the data base shown in Table II. We also assume that we have obtained a radiograph of an animal from which we wish to estimate bone-age and that this radiograph indicated that both B and C were closed and A was open. The first step is to compute the probability that configuration will occur at each age, as shown in Table III. These probabilities are products of the probability that A is open (which is one minus the

**Table I.** Closed epiphyseal junctions in various age groups (hypothetical data)

Age (months)	0-3	3-6	6-9	9-12	12-15	15-18	18-21	21-24
Epiphysis A	0 <sup>1</sup>	0	1	1	3	4	4	5
Epiphysis B	0	3	3	5	5	5	5	5
Epiphysis C	0	0	1	3	4	5	5	5

Total number of animals in each age group = 5.

<sup>1</sup>This number indicates the number of animals in the 0-3 months age group that had a closed (or fusing) junction at epiphysis A.

**Table II.** Pooled probabilities of closed epiphyseal junctions as a function of age<sup>1</sup>

Age (months)	3	6	9	12	15	18	21	24
Epiphysis A	0 <sup>2</sup>	0.1	0.2	0.4	0.7	0.8	0.9	1.00
Epiphysis B	0.2	0.6	0.8	1.00	1.00	1.00	1.00	1.00
Epiphysis C	0	0.1	0.4	0.7	0.9	1.00	1.00	1.00

<sup>1</sup>Hypothetical data from Table I.

<sup>2</sup>This number represents the pooled probability.

**Table III.** Sample bone-age probability calculation (hypothetical)

Age (months)	3	6	9	12	15	18	21	24
Probability A is open and B and C are closed	0.0	0.05	0.26	0.42	0.27	0.20	0.10	0.0

probability that A is closed), the probability that B is closed, and the probability that C is closed. [Actually,  $P(A = \text{open} \mid B = \text{closed} \mid C = \text{closed}) = P(A = \text{open}) P(B = \text{closed} \mid A = \text{open}) P(C = \text{closed} \mid A = \text{open} \mid B = \text{closed})$ . These conditional probabilities are almost impossible to assess when a large number of different epiphyses are to be used in the calculation. To simplify the process, we treat the probabilities as though they were independent. The practicality of this simplification is demonstrated in the Results section.] For example, at 9 months, the probability that this configuration will occur is  $(1 - 0.2) \times (0.8) \times (0.4) = 0.26$ .

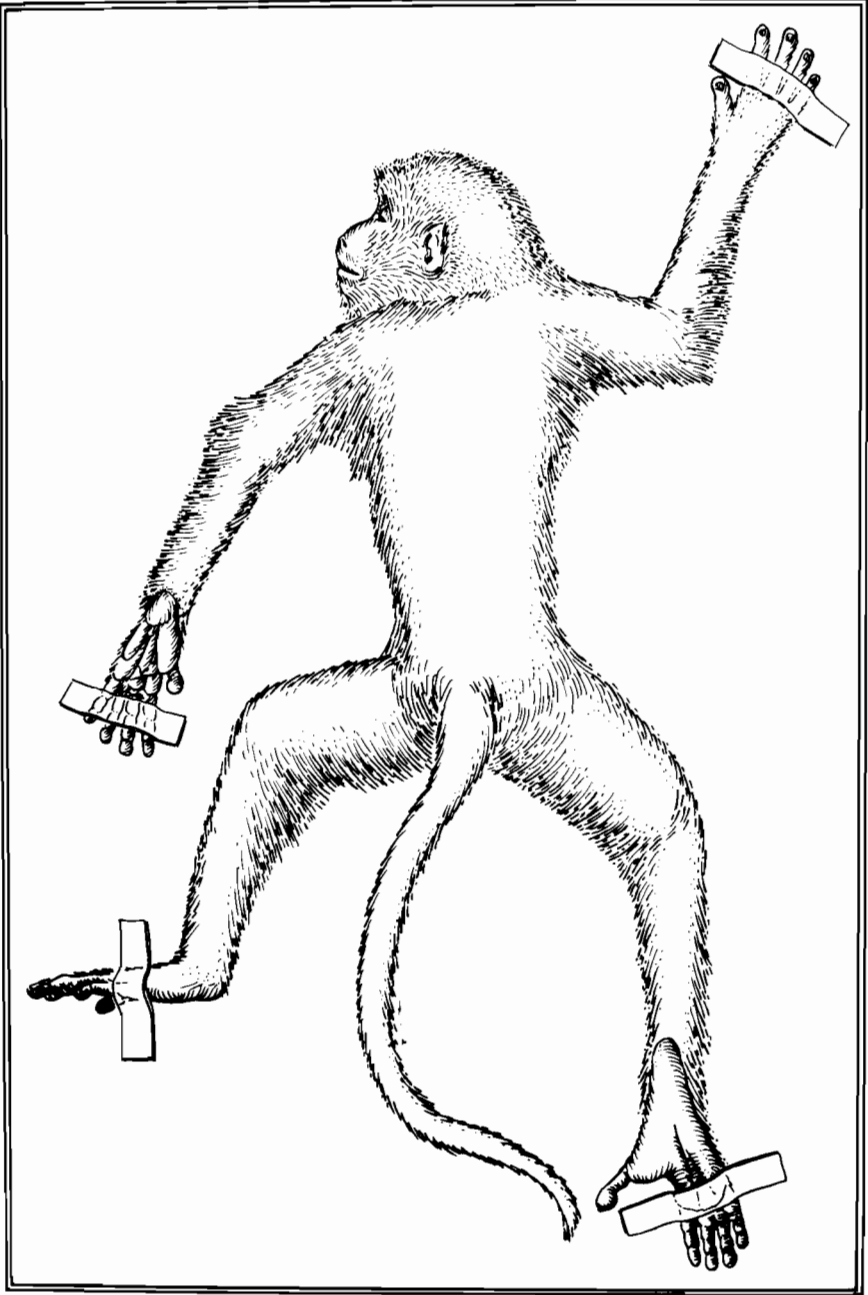
The second step is to compute a weighted mean estimate of the bone-age. This is done by multiplying each age by its probability, summing these products, and dividing by the sum of the probabilities. In this example, the age estimate would be  $(6 \times 0.05 + 9 \times 0.26 + 12 \times 0.42 + 15 \times 0.27 + 18 \times 0.20 + 21 \times 0.10) / (0.05 + 0.26 + 0.42 + 0.27 + 0.20 + 0.10) = 13.4$  months.

In actual practice, the computer program permits updating the data base at any time with the acquisition of new data from animals of known age. Included in this data base is information on a large number of different epiphyses and sesamoids. The program permits the user to select which of these are to be used for actual bone-age estimation. The investigator simply notes the state of each epiphysis (open or closed) and the state of each sesamoid (present or absent). This information is entered into the computer, which then computes an estimated age based on probabilities contained in the data base.

**Animals.** Ninety radiographs from a group of 59 normal, age-known, male monkeys (*M. fascicularis*) formed the data base that was used to test the analytic technique. Thirty-six of the monkeys were born and raised at the Regional Primate Research Center at the University of Washington. Radiographs from the other 23 animals were obtained from the University of Illinois, the University of Texas, the Wisconsin Regional Primate Research Center, and the Oregon Regional Primate Research Center. To be certain of their ages, only animals born in these colonies were included. Ages of the animals ranged from 0.7–41.8 months.

**Radiographic Procedures.** Radiographic examinations were carried out according to the published methodology (4), with some modification. The animals were sedated and placed in a prone position as shown in Figure 1. Their elbows were semiflexed, the right hand was taped to the cassette with the palmar surface down, and the left hand was taped with the palmar surface up. The right and left knees were also semiflexed, with the right flexed less than the left. The right foot was taped with its volar surface up, and the left foot was taped for a lateral view.

The epiphysal junctions examined were the humerus (proximal, distal, and medial epicondyle), radius (distal and proximal), ulna (distal and proximal), carpals, metacarpals, phalanges (proximal), os coxae (acetabulum), femur (proximal, distal, and lesser trochanter), patella, fabella, tibia (proximal, and distal tuberosity), fibula (proximal and distal), tarsals, calcaneus, metatarsals, and phalanges (proximal). The sesamoids examined were the radial carpal, first carpal, lateral tarsal, medial tarsal, first digital proximal, first digital distal, fifth digital, and second through fourth digital. Epiphyses were scored as either open or closed. Fusing functions were considered closed. Sesamoids were scored as either present or absent.



**Fig. 1.** Animal placement for taking radiographs used in the determination of bone-age. See text for details.

## Results and Discussion

Of the 33 epiphyses and sesamoids scored in the study, 13 were selected to be used for estimating bone ages. The other 20 either closed later than 40 months and therefore couldn't be used because our data base did not extend beyond this age ( $n = 9$ ), or had erratic probability distributions ( $n = 11$ ). The data base used is shown in Table IV.

To verify the validity of the computational procedure, data from 52 of the 90 original x-rays were re-entered as unknowns and bone-ages were calculated. The results are illustrated in Figure 2. The correlation ( $r$ ) between the calculated age and estimated age was 0.95. The average absolute difference was 2.6 months (23 underestimates and 28 overestimates). In the youngest animals, as expected, the estimated ages were clustered at one value (3.8 months). At this age all of the epiphyses are open and all of the sesamoids are absent. Until the animal becomes old enough for the first epiphysis to close, the estimated age will remain at this value. Such clustering does not occur in older animals, which have a larger variety of open and closed configurations.

The differences between the estimated and actual ages, shown in Figure 2, can be accounted for by a combination of the following factors. First, there are differences between animals in their rate of skeletal development. Second, there were, no doubt, some errors that occurred in reading the radiographs. Third, there are limitations in resolution due to the discrete (rather than continuous) method of scoring the epiphysial configurations and computing estimated age. Finally, there is probably some error in the calculation due to the conditional nature of the probabilities. Although it is not possible to ascertain the relative contributions of each of these error sources of variability, the fact that actual and estimated ages agree within 2.6 months, on the average, suggests that errors generated in the actual estimation process are relatively small.

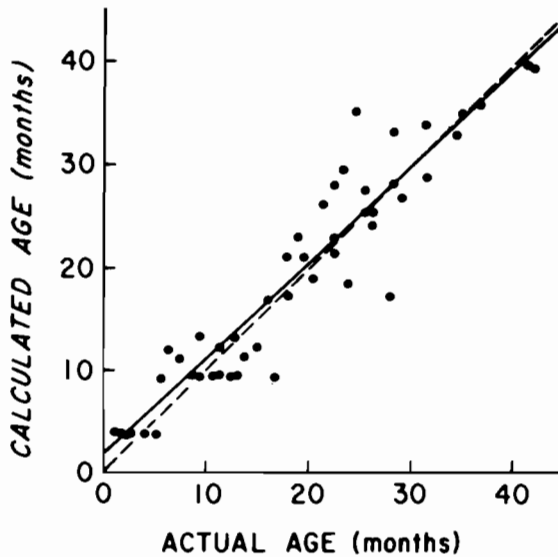
As a test of the effects of interobserver variability on bone age estimation, two individuals independently scored 10 x-rays. One scorer had a considerable amount of experience in reading and scoring; the other was completely inexperienced in reading radiographs. As shown in Table V, the two agreed well with each other. The average absolute difference was only 1.9 months.

We have used this technique in the male *M. fascicularis*. With the appropriate data base, the methodology could be applied to other primate species, since the sequence of epiphysial closure is similar among primate species and is even characteristic in the majority of mammals, including the cat and pig (5). Each sex must be considered independently, since they develop at different rates.

**Table IV.** Pooled closure probabilities as a function of age in the *Macaca fascicularis*

Age (months)	3	6	9	12	15	18	21	24	27	30	33	36	39	42
Distal humerus	0.0	0.0	0.0	0.05	0.15	0.07 <sup>1</sup>	0.21	0.31	0.41	0.50	0.66	1.00	1.00	1.00
Proximal ulna	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.20	0.33
Radial carpal	0.0	0.0	0.0	0.0	0.0	0.0	0.15	0.25	0.33	0.33	0.42	0.75	0.80	0.83
First carpal	0.0	0.0	0.0	0.0	0.07	0.23	0.42	0.31	0.41	0.70	0.75	1.00	1.00	1.00
Proximal femur	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.25	0.60
Patella	0.18	0.80	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Fabella	0.0	0.0	0.0	0.0	0.0	0.07	0.38	0.66	0.81	0.87	1.00	1.00	1.00	1.00
Tibial tuberosity	0.0	0.0	0.0	0.0	0.07	0.15	0.15	0.20	0.25	0.20	0.25	0.25	0.80	1.00
Tarsals	0.0	0.0	0.15	0.29	0.41	0.41	0.42	0.50	0.54	0.44	0.50	0.50	0.80	1.00
Calcaneus	0.0	0.06	0.09	0.06	0.08	0.23	0.28	0.18	0.08	0.20	0.37	0.50	1.00	1.00
1st digital (proximal)	0.0	0.0	0.0	0.05	0.18	0.33	0.66	0.62	0.58	0.70	0.87	1.00	1.00	1.00
5th digital	0.0	0.0	0.0	0.0	0.0	0.09	0.27	0.30	0.36	0.40	0.42	0.66	0.80	0.83
2nd-4th digital	0.0	0.0	0.0	0.0	0.08	0.18	0.66	0.85	0.81	0.85	1.00	1.00	1.00	1.00
Pooled number of radiographs at each age	16	15	22	17	13	13	14	16	12	10	8	4	5	6

<sup>1</sup>Ideally the closure probabilities should not decrease with age, but variability due to small sample sizes and possible scoring errors caused occasional minor decrements.



**Fig. 2.** Relationship between chronological age and computer-assessed bone-ages for 52 different age determinations. The dashed line represents the ideal case (1:1 correspondence between chronological age and bone-age). The solid line indicates the actual least squares regression for all of the data points (slope = 0.94, intercept = 1.82,  $r = 0.95$ ).

**Table V.** Comparison of bone age estimates between two different scorers

Actual age	28.2	9.1	17.6	36.5	28.2	28.8	25.4	15.0	22.4	19.8
Scorer 1 (experienced)	28.4	13.2	21.1	36.0	33.3	26.9	25.4	13.2	21.5	19.1
Scorer 2 (inexperienced)	27.4	9.5	21.5	34.2	33.3	27.6	21.1	14.6	17.9	21.1

There are several potential advantages associated with the implementation of this technique in studies of primate development. First, since no fine distinctions are made concerning the state of epiphysial development (the centers could be read as simply present or absent), scoring is quite easy and can be handled by technical personnel with very little training. Second, bone-age is calculated automatically, objectively, and immediately. For most bone-age estimates, this procedure is much simpler than those used presently and may prove to be more accurate.

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