

Study of age dependence of epiphyseal ossification of the hand skeleton

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Received: 11 June 2007 / Accepted: 4 September 2007 / Published online: 5 October 2007
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Abstract Radiological analysis of the hand skeleton is a key pillar of forensic age diagnostics in living subjects undergoing criminal proceedings. The present study investigated whether ossification stage classification of selected epiphyses of the hand could provide added value to hand radiograph analysis. Hand radiographs from 265 male and 164 female subjects aged 10–18 years old who had been X-rayed due to traumatological indications were therefore assessed. Epiphyseal ossification of selected elements of the hand skeleton (ulna, radius and third metacarpal, basal phalanx, mesophalanx and telephalanx) was graded based on the criteria of the five-stage classification system of Schmeling et al. (Int J Legal Med, 118:5–8, 2004) for clavicular epiphyseal cartilage. Stage 5 (absence of the epiphyseal scar) does not occur in the radius of men before the age of 18. Stage 5 can therefore be regarded as a potential parameter for valid determination of a minimum age of 18 years for forensic age estimation in criminal proceedings.

Keywords Forensic age estimation · Skeletal age · Hand ossification

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Introduction

Forensic age estimation of living subjects undergoing criminal proceedings has become a major research area in forensic science during the last few years [1, 2, 7, 9, 14–17]. In these cases, the investigated subjects are nonnationals of critical age who lack valid identification documents, and forensic age estimation is necessary to decide whether these persons should be tried as juveniles or adults.

The ages of relevance to criminal liability ranges between 14 and 18 years in most countries [3].

According to the recommendations of the AGFAD (Arbeitsgemeinschaft für Forensische Altersdiagnostik, Study Group on Forensic Age Diagnostics), forensic age estimates in living subjects for purposes of medical jurisprudence should be based on the combined examination findings in three independent development systems. Physical maturity is thereby assessed based on an appraisal of anthropometric parameters, secondary sexual characteristics, and relevant age-related developmental disorders. Dental development is assessed by means of a dental examination, which should include inspection of the oral cavity and analysis of an orthopantomogram. Skeletal maturity is evaluated by radiological analysis of the left hand. If it is uncertain whether the subject has reached the age of 21, a conventional radiological or computer tomographic examination of the clavicles should additionally be performed to augment the analytical spectrum [12].

Two fundamentally different procedures are used for radiological assessment of skeletal development of the hand. The single bone method is performed by analyzing the degree of maturity of selected skeletal elements [10, 19]. In the atlas method, the bone age estimate is obtained by comparing an X-ray of the test subject's hand with age and sex-matched standard radiographs [20].

The present study investigated whether ossification-stage classification of selected epiphyseal centers of the hand could provide added value to hand-radiograph analysis.

Materials and methods

Hand radiographs from 164 female and 265 male subjects aged 10–18 years old were analyzed retrospectively. Table 1 shows the age (chronological) and sex distribution of the patient population. All of the hand X-rays were made between 1983 and 2002 at various hospitals in Berlin and Leipzig, Germany from patients with traumatological indications. All patients included in the study were children and adolescents exhibiting age-appropriate physical development. Subjects with signs and symptoms of diseases that affect bone development were excluded from the study.

The epiphyseal ossification stage was determined for the following elements of the hand skeleton: the distal radius, the distal ulna, the third metacarpal bone, the third basal phalanx, the third mesophalanx, and the third telephalanx. Staging was performed based on the criteria of the five-stage classification system developed by Schmeling et al. [13] for characterization of clavicular ossification:

- Stage 1: Non-ossified ossification center
- Stage 2: Ossified ossification center with nonossified epiphyseal cartilage
- Stage 3: Partially ossified epiphyseal cartilage
- Stage 4: Fully ossified epiphyseal cartilage with discernable epiphyseal line
- Stage 5: Nondiscernable epiphyseal line.

Results

Tables 2 and 3 present the statistical data on the course of epiphyseal ossification over time for all target elements of the hand skeleton in men and women, respectively.

Table 1 Age and sex distribution of the patient population

Chronological age (years)	Women	Men
10	19	19
11	13	22
12	24	30
13	17	32
14	15	31
15	23	29
16	23	24
17	14	24
18	12	30
Σ	164	265

Table 2 Statistical parameters in years for women

Skeletal element-stage	Mean; SD	LQ; median; UQ	Minimum; maximum
Radius			
Stage 1	–	–	–
Stage 2	10.9; 0.7	10.4; 10.9; 11.3	10.1; 13.0
Stage 3	13.1; 1.5	12.1; 12.8; 13.9	10.1; 17.8
Stage 4	16.5; 1.4	15.6; 16.6; 17.5	12.9; 19.0
Stage 5	17.8; 1.2	16.6; 18.1; 18.8	16.2; 19.0
Ulna			
Stage 1	11.1; 0.5	10.7; 11.1; 11.5	10.7; 11.5
Stage 2	11.1; 0.8	10.4; 11.0; 11.5	10.1; 13.0
Stage 3	13.5; 1.4	12.4; 13.4; 14.2	10.6; 17.8
Stage 4	15.6; 1.1	14.8; 15.8; 16.5	13.6; 17.0
Stage 5	17.0; 1.2	16.0; 16.9; 17.8	13.9; 19.0
Metacarpal III			
Stage 1	–	–	–
Stage 2	11.0; 0.8	10.2; 10.9; 11.5	10.1; 13.0
Stage 3	12.4; 1.3	11.5; 12.3; 13.2	10.2; 15.5
Stage 4	14.5; 1.5	13.4; 13.9; 15.7	12.3; 17.8
Stage 5	16.6; 1.4	15.6; 16.6; 17.7	12.9; 19.0
Basophalanx III			
Stage 1	11.0; 0.0	11.0; 11.0; 11.0	11.0; 11.0
Stage 2	11.0; 0.8	10.2; 10.8; 11.5	10.1; 13.0
Stage 3	12.7; 1.2	12.1; 12.5; 13.5	10.6; 15.5
Stage 4	15.8; 1.5	14.7; 15.8; 16.8	12.3; 18.7
Stage 5	17.4; 1.4	16.8; 17.7; 18.4	13.8; 19.0
Mesophalanx III			
Stage 1	–	–	–
Stage 2	11.1; 0.7	10.5; 11.0; 11.7	10.1; 12.5
Stage 3	13.1; 1.6	12.2; 12.9; 14.0	10.2; 17.8
Stage 4	15.5; 1.3	14.6; 15.8; 16.6	11.6; 18.0
Stage 5	17.1; 1.7	16.5; 17.7; 18.5	12.9; 19.0
Telephalanx III			
Stage 1	–	–	–
Stage 2	11.2; 0.7	10.6; 11.1; 11.7	10.1; 12.5
Stage 3	12.1; 1.2	11.3; 12.3; 12.9	10.1; 14.2
Stage 4	15.5; 1.7	14.2; 15.7; 16.6	11.6; 19.0
Stage 5	16.1; 2.0	14.4; 16.7; 17.8	10.6; 19.0

SD Standard deviation; LQ lower quartile; UQ upper quartile

The median chronological age of men and women was found to increase with increasing ossification stage in all skeletal elements analyzed.

The difference between the median ages of men and women also decreased with increasing ossification stage to varying degrees. Consequently, boys increasingly made up for the initial maturity advance in girls with increasing skeletal maturity.

Comparison of the course of epiphyseal ossification over time revealed only slight sex-independent differences in age for reaching the lower stages of ossification. The higher stages were associated with increasing age differences. Complete epiphyseal ossification and scar disappearance occurred earliest in the third metacarpal and the third

Table 3 Statistical parameters in years for men

Skeletal element-stage	Mean; SD	LQ; median; UQ	Minimum; maximum
Radius			
Stage 1	10.8; 0.7	10.2; 10.6; 10.8	10.1; 12.3
Stage 2	12.3; 1.2	11.5; 12.1; 13.2	10.1; 15.8
Stage 3	14.4; 1.2	13.4; 14.4; 15.2	12.2; 18.0
Stage 4	17.2; 1.3	16.4; 17.6; 18.4	14.5; 18.9
Stage 5	18.8; 0.2	18.7; 18.8; 19.0	18.7; 19.0
Ulna			
Stage 1	11.1; 1.3	10.2; 10.5; 11.7	10.1; 14.3
Stage 2	12.5; 1.4	11.3; 12.2; 13.3	10.3; 15.8
Stage 3	13.9; 1.1	12.9; 14.0; 14.7	12.0; 16.4
Stage 4	16.6; 1.3	15.2; 16.7; 17.7	14.5; 18.8
Stage 5	18.0; 0.9	17.6; 18.3; 18.7	15.2; 19.0
Metacarpal III			
Stage 1	11.2; 0.8	10.4; 11.6; 11.9	10.1; 12.2
Stage 2	12.1; 1.2	11.1; 12.1; 13.0	10.1; 14.8
Stage 3	14.1; 1.1	13.2; 13.9; 15.0	12.0; 16.7
Stage 4	15.4; 1.2	14.5; 15.1; 16.4	13.8; 18.0
Stage 5	17.4; 1.2	16.6; 17.8; 18.5	14.7; 19.0
Basophalanx III			
Stage 1	11.2; 1.1	10.3; 10.7; 12.1	10.1; 13.3
Stage 2	12.5; 1.3	11.6; 12.6; 13.2	10.1; 15.8
Stage 3	14.6; 1.1	13.7; 14.6; 15.3	12.4; 17.7
Stage 4	16.9; 1.4	15.6; 17.0; 18.0	14.2; 18.9
Stage 5	17.9; 1.1	17.5; 18.4; 18.6	14.9; 19.0
Mesophalanx III			
Stage 1	10.4; 0.3	10.2; 10.5; 10.7	10.1; 10.7
Stage 2	12.5; 1.3	11.6; 12.4; 13.2	10.1; 15.8
Stage 3	14.8; 1.2	13.8; 14.8; 15.5	12.4; 17.9
Stage 4	15.6; 1.5	14.4; 15.3; 16.7	13.0; 18.7
Stage 5	17.4; 1.2	16.7; 17.8; 18.4	14.7; 19.0
Telephalanx III			
Stage 1	11.0; 0.9	10.2; 10.6; 12.3	10.1; 12.3
Stage 2	12.4; 1.4	11.2; 12.3; 13.2	10.1; 15.8
Stage 3	14.1; 1.3	13.1; 14.0; 14.8	11.8; 17.9
Stage 4	15.7; 1.7	14.8; 15.4; 16.5	13.0; 18.7
Stage 5	17.2; 1.4	16.2; 17.5; 18.3	14.2; 19.0

SD Standard deviation; LQ lower quartile; UQ upper quartile

telephalanx. The distal radial epiphysis reached ossification stages 4 and 5 at a much later age.

The chronological sequence of minimum age for reaching stage 5 of epiphyseal ossification, which corresponds to the forensically critical minimum ages, was sex-independent. Chronologically, stage 5 is first reached in the third telephalanx, then in the third mesophalanx/metacarpal, the third basophalanx, the ulna, and finally in the radius.

The relatively high minimum age of occurrence of stage 5 in the radius is a decisive difference between this bone and all other hand bones studied. Epiphyseal ossification of 76 out of a total of 78 radiographs of the hands of men aged 16, 17, and 18 years old was classified as either stage 3 or 4. Since this group included all 48 of the 16- and 17-year-olds,

none were classified as stage 5 in this group. The other 28 men in this group exhibited a chronological age of 18 years. In the two remaining cases, stage 5 was diagnosed at a minimum age of 18.6 years.

In the female subjects, stage 5 occurred earlier, at an age of 16.2 years.

Discussion

The provision of forensic proof that a living subject has reached the age of 18 years old is a great diagnostic challenge, particularly in medical jurisprudence. In both sexes, the signs of sexual maturity are already fully developed by this time and cannot be used for further age differentiation [5, 6, 18]. At stages 4 and 5, the degree of ossification of the clavicular epiphysis provides reliable evidence that a person has reached the age of 18. However, the minimum age of reaching stage 4 is 2 years over this age limit in women and 3 years over the limit in men [13]. Parameters of tooth development are not generally suited for determining whether a person has reached the minimum age of 18 years old [4, 8, 9]. The available hand-skeleton-based methods of age determination also do not provide sufficiently reliable evidence that a person is at least 18 years of age for legal purposes [14].

Schmelting et al. [13] used parameters of epiphyseal ossification, which are fundamental criteria for assessment of hand radiographs, as the basis for further differentiation of clavicular ossification, the final stage of which was stage 4 until then. In most cases, an ossified remnant of the former epiphyseal cartilage is discernable for a limited time only over the course of ossification of the medial epiphysis of the clavicle. The corresponding mark is no longer discernable in the newly defined stage 5. The minimum age for reaching stage 5 is 6 years above the minimum age for stage 4 in women and 5 years higher in men. This led to the question of whether corresponding studies of the temporal course of epiphyseal ossification of the hand skeleton would yield a similar differentiation for reliable forensic evidence that a person has reached the age of 18 years old.

Compared to the established atlas and single-bone methods, which are based on a combination of different criteria for analysis of hand radiographs, singular assessment of the epiphyseal ossification process extended the range of age diagnosis, as was expected. By expanding the range of epiphyseal ossification classification stages used in the established methods, the new age-estimation method is possibly the first to provide valid evidence that a person has reached the minimum age of 18 years old for criminal prosecution purposes. Ossification stage 5 characterized by

disappearance of the radial epiphyseal scar did not appear in men before the age of 18 years old in our investigation.

According to the current state of knowledge, ethnic origin does not have a significant influence on skeletal maturation in the age group of interest [11]. The degree of modernization of a population, however, was reliably shown to affect the ossification rate. Next to this, the degrees of economic and medical advancement are other key factors in the bone-age acceleration process [15]. The application of reference data to populations with a lower degree of modernization will lead to underestimation of chronological age in the majority of cases. This poses no disadvantage to an individual facing criminal charges.

The present study does not permit any further statistical characterization of stages 4 and 5 of epiphyseal ossification. Further studies that include a larger number of subjects especially such over 18 years of age should therefore be performed.

Acknowledgements The authors wish to thank PD Dr. R. Fuchs (Berlin), Prof. Dr. F. Schmidt (Leipzig), and PD Dr. G. Stobbe (Berlin) for kindly providing the hand radiograms.

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