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ORIGINAL ARTICLE

The digital atlas of skeletal maturity by Gilsanz and Ratib: a suitable alternative for age estimation of living individuals in criminal proceedings?

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Abstract As a collection of radiographic standards of the normal hand development with a homogenous degree of maturity of all skeletal elements, the digital atlas of skeletal maturity by Gilsanz and Ratib combines the possibilities of digital imaging with the principle of a conventional atlas method. The present paper analyses the forensic applicability of skeletal age assessment according to Gilsanz and Ratib to age estimation in criminal proceedings. For this, the hand X-rays of 180 children and adolescents aged 10–18 years old were examined retrospectively. For the entire age range, the minima and maxima, the mean values and standard deviations as well as the medians with upper and lower quartiles are specified by sex. For the legally relevant age groups from 14 to 18 years, there is a risk of overestimation of the chronological age of up to 7.2 months in females. The method of Gilsanz and Ratib is therefore only suitable to forensic age estimation in criminal proceedings to a limited extent.

Keywords Forensic age estimation · Bone age · Hand skeleton

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Introduction

Shortly after Wilhelm Conrad Röntgen discovered X-rays in 1895, the first systematic studies on the assessment of skeletal maturity as a measure of biological development processes were published [2]. To date, bone age assessments have been established in clinical radiology, above all in the diagnosis of growth disorders [7, 35] and to predict the prospective adult height [1, 35].

It is only in recent years that the application of skeletal age assessment in forensic age estimation in criminal proceedings has become more and more important [16, 36]. Here, it contributes to the legal review of a given age of criminal responsibility and/or applicability of criminal law for adults. In most countries, the relevant age limits are between 14 and 18 years [5].

In the criminal context, particularly high demands are made on the reliability of an age diagnosis. Therefore, for this kind of expert reports, the international and interdisciplinary Study Group on Forensic Age Diagnostics (http://rechtsmedizin.klinikum.uni-muenster.de/agfad/index.htm) recommended a combination of a skeletal age assessment with the help of an X-ray of the hand and, if applicable, the inner clavicular joints with an assessment of physical and odontostomatological signs of maturity [18]. Regarding the assessment of bone maturity, the hand skeleton is most important by far until its development is completed at the age of about 18 years.

Furthermore, the specific requirements in criminal law caused a rapidly increasing importance of age estimation research within forensic sciences [3, 8-10, 15, 17, 21-23, 26, 27]. In particular, in the field of skeletal age assessment, various methods long proven in clinical application could be reviewed and possibly be adapted to be used in forensics [16, 20, 24, 25].

Nowadays, the classical atlas methods of Greulich and Pyle [7] and/or Thiemann, Nitz and Schmeling [36] are primarily used to assess bone age by means of an X-ray of the hand.

The methods of modern digital imaging and image analysis offered for the first time the opportunity of an automated extraction of radiomorphologic information that is relevant to the skeletal age assessment of the hand [4, 11, 34]. These methods provided the prospect of objectivising an estimation result due to independence of the examiner's individual knowledge and experience. Approaches of such a computer-based age diagnosis have not yet been able to gain acceptance due to the extraordinary anatomical-physiological complexity and variability of the developmental processes in the hand skeleton.

Using the digital atlas of skeletal maturity of Gilsanz und Ratib [6], which was published in 2005, the authors provided a different approach. Taking the frequently inhomogeneous development of individual bones of the hand skeleton into consideration, they presented 58 artificial, idealised, sex- and age-specific standards of bone development. A specially developed software, which can also be implemented on Portable Digital Assistants (PDAs), is claimed to provide a practicable alternative to the traditional reference books.

The present study is the first one to analyse the forensic applicability of the skeletal age assessment method of Gilsanz and Ratib to age estimation in criminal proceedings.

Subjects and methods

A total of 180 radiographs of the left hand of 90 male and 90 female subjects aged between 10 and 18 years were evaluated retrospectively. For each sex, ten radiographs were analysed for each completed year of life. The hand X-rays had been taken between 1983 and 2002 in an orthopaedic practice in Papenburg, Germany as well as in several hospitals in Berlin and Leipzig, Germany.

The assessment only involved hand radiographs of children and adolescents with age-appropriate physical development. Subjects who displayed signs of a disease affecting skeletal maturation were excluded from the study.

It can be assumed that the subjects of the examined collective represent the average composition of the German population in their age group.

The hand X-rays were available in digitised form on a scale of 1:1. The respective skeletal age according to the digital atlas method of Gilsanz and Ratib was assessed by means of sex-specific and age-standardised idealised comparative radiographs using both the computer-based version and the text book. All evaluations were made by one examiner experienced in the area of skeletal age determination. The statistical analysis of the collected data was carried out with the help of SPSS (version 12).

Results

Tables 1 and 2 show the statistical measures of the study group obtained for the stages of skeletal age between 9 and 18 years by sex. The respective minima and maxima, the mean values and their standard deviations as well as the medians with upper and lower quartiles are listed. There was no male subject with a skeletal age of 9 years.

The data obtained show for both sexes that within the entire observed age interval, the mean values and medians of the chronological age increased with increasing skeletal age. Thus, they demonstrate high congruency between the estimated ages by Gilsanz-Ratib and the chronological ages of the subjects.

The standard deviations ranged between 0.2 and 1.0 years in the girls and between 0.5 and 1.2 years in the

Table 1 Measurement data of chronological age for the female sex

Skeletal age (years)	Minimum (years)	Maximum (years)	Mean value (years)	Standard deviation (years)	Lower quartile (years)	Median (years)	Upper quartile (years)
9	10.0	10.3	10.2	0.2	10.0	10.2	10.3
10	10.1	12.2	11.0	0.6	10.5	10.9	11.4
11	10.2	13.1	11.8	0.9	11.1	11.8	12.6
12	11.6	14.2	12.8	0.9	12.2	12.5	13.6
13	12.1	13.5	12.9	0.7	12.1	13.0	13.5
14	12.6	16.2	13.9	1.0	13.2	13.8	14.5
15	13.3	16.2	15.1	0.8	14.6	15.1	15.7
16	14.3	16.6	15.4	0.8	14.8	15.4	16.0
17	15.5	18.7	17.1	0.9	16.4	16.9	17.8
18	17.2	18.9	18.1	0.5	17.7	18.2	18.6

Table 2 Measurement data of chronological age for the male sex

Skeletal age (years)	Minimum (years)	Maximum (years)	Mean value (years)	Standard deviation (years)	Lower quartile (years)	Median quartile (years)	Upper quartile (years)
9	–	–	–	–	–	–	–
10	10.1	11.0	10.4	0.5	10.1	10.2	11.0
11	10.4	12.4	11.2	0.6	10.7	11.1	11.6
12	10.3	13.1	11.5	1.2	10.4	11.4	12.7
13	11.2	14.6	12.8	1.1	11.9	12.5	14.0
14	12.7	15.9	14.1	1.0	13.3	13.8	15.1
15	14.8	16.4	15.5	0.7	14.9	15.2	16.3
16	15.8	17.9	16.5	0.8	16.0	16.1	17.2
17	15.8	18.3	17.1	0.9	16.1	17.3	17.8
18	16.6	18.9	18.1	0.8	17.6	18.4	18.8

boys. Values between 0.3 and 1.5 years in female subjects and between 0.9 and 2.3 years in male subjects were obtained for the interquartile ranges.

In the skeletal age range between 14 and 16 years, which is of particular forensic relevance for the determination of age of criminal responsibility, simple standard deviations ranged between 0.8 and 1.0 and the interquartile ranges amounted to between 1.1 and 1.3 years in the female group. In the examined female subjects above a skeletal age of 15 years, the lower quartile of the chronological age reached values over 14.0 years. The minimum of the chronological age was higher than 14.0 years within this collective with a skeletal age of at least 16 years.

The skeletal age of 18 years, which is relevant to the possible applicability of criminal law for adults, showed a lower quartile of 17.7 years and a minimum of 17.2 years in the female subjects.

In the girls, the differences between skeletal age and mean value of the chronological age in the legally relevant age groups of 14–18 years ranged between −0.1 and +0.6 years. Negative values were obtained if the mean value of the chronological age was higher than the respective skeletal age.

For the boys, in the age group from 14 to 16 years, the simple standard deviation ranged from 0.7 to 1.0 and the interquartile ranges amounted to between 1.2 and 1.8 years. In the examined male subjects beyond a skeletal age of at least 15 years, both the lower quartile and the minimum of the chronological age reached values over 14.0 years.

For a skeletal age of 18 years, a lower quartile of 17.6 years and a minimum of 16.6 years were calculated.

In the boys, the differences between skeletal age and mean value of the chronological age in the legally relevant age group of 14 to 18 years ranged between −0.5 and −0.1 years.

Discussion

The possibility of sequentially examining the maturation-related changes in the skeletal system by means of X-rays led to the first scientific systematic analysis of ossification processes with the help of hand radiographs even in 1897 [2]. Within a short period of time, fundamental knowledge of the development of the skeletal elements of the hand was obtained [12, 29-31].

Since 1935, various radiographic atlases have been published illustrating the normal ossification of the human hand [e.g. 7, 14, 19, 28, 36, 37]. They enable the estimation of the chronological age of a child or an adolescent by comparing the entire maturation pattern of a given hand radiograph with a collection of standard images.

Although the different ossification centres of the hand skeleton appear in a certain regular order and the changes in size and shape as well as the ossification of the epiphyseal cartilages take place more or less regularly, hand radiographs with diverging maturation patterns are occasionally to be evaluated. This phenomenon is considered more thoroughly in another methodical approach. With the help of the so-called single-bone method [13, 32, 33, 35] the individual chronological age can be estimated by means of the degree of maturity of selected skeletal elements in a hand radiograph.

The digital atlas of skeletal maturity by Gilsanz and Ratib [6] comprises a total of 58 age- and sex-specific comparative radiographs of the normal development of the hand skeleton. Using the possibilities of modern digital imaging and image processing, the authors created artificial radiographs which combine different images of skeletal elements with identical degrees of maturity to an idealised standard. Thus, the Gilsanz-Ratib method unites the potential of digital imaging with the principle of a conventional atlas method.

The work of Gilsanz and Ratib [6] is based on extensive studies on standard skeletal development having been performed in the paediatric clinic in Los Angeles since the mid-1980 s. The defined reference population comprises solely of Caucasian children and adolescents with age-appropriate physical development and without chronic diseases or long-term medication. The hand radiographs of a total of 261 male and 261 female study participants were assigned to 29 age groups between 8 months and 18 years according to their bone age. The intervals between the age groups were between 2 and 4 months until a skeletal age of 2.5 years, 6 months until a skeletal age of 3–6 years and 12 months until a skeletal age of 18 years. Within the defined age groups with hand radiographs of the same sex and bone age, two radiologists independently analysed six different anatomic regions: the distal, medial and proximal phalanges, the metacarpal bones and carpal bones as well as the distal parts of radius and ulna. The nine radiographs of each age group were assigned to a concrete skeletal region with regard to the exact degree of maturity. The fifth image in ascending order represented the mean degree of maturity of this region. This way, within each age group, two to six images could be identified which were optimised in terms of background and size, contrast and intensity as well as osseous outline. Finally, using the selected hand radiographs, the individual ossification centres with average stages of development were combined to generate into a virtual radiographic standard of the respective skeletal age.

The present study is the first to analyse the forensic applicability of the digital atlas of skeletal maturity by Gilsanz and Ratib to age estimation in living individuals in criminal proceedings. First of all, the results confirm the close correlation between skeletal age and chronological age of the subjects. In the age range between 14 and 16 years, which is decisive for assessing criminal responsibility, simple standard deviations of 0.7–1.0 years were obtained. In the same age interval, the simple standard deviations are indicated to range between 0.3 and 1.7 years for the atlas method of Greulich and Pyle [24] and between 0.2 and 1.2 years for the atlas method of Thiemann and Nitz [16]. With an almost normally distributed skeletal age, the standard deviation of the mean value is to be regarded as a measure of accuracy of an estimation method. Thus, the accuracy of the Gilsanz–Ratib method and the established atlas methods can be assumed to be comparable. Differences between the maximum values and the mean standard deviations can primarily be attributed to a relatively small number of cases of the present study.

According to the values of the lower quartiles obtained for the skeletal age groups in both sexes, at least 75% of all subjects examined with a skeletal age of 15 years had completed 14 years of age. Taking the absolute minima into consideration, in females, the diagnosis of a skeletal age of 16 years and in males a skeletal age of 15 years is required to make the legally relevant statement that an individual has completed the 14 years of age. These measures also largely correspond to the values of the Greulich–Pyle method [24] and/or the Thiemann–Nitz–Schmeling method [20].

The results of this study also show that in the diagnosis of a legally relevant bone age of 18 years, a chronological age of at least 17.2 years in women and of at least 16.6 years in men is possible. If the skeletal development of the hand is completed, a legally reliable verification that an individual has reached the age of 18 years is therefore principally only possible in the recommended combination with the results of other developmental systems. This also applies to the atlas methods established in age estimation in criminal proceedings.

According to the available results, the differences between the skeletal age and the mean value of the chronological age in the legally relevant age groups ranged between −0.1 and +0.6 years in female subjects and between −0.5 and −0.1 years in male subjects. The values were positive if the obtained skeletal age was higher than the mean value of the chronological age. Thus, if the skeletal age assessment method of Gilsanz and Ratib is applied to girls and women, there is a risk of age overestimation of up to 7.2 months. This forensically significant difference compared to the conventional atlas methods of Greulich and Pyle as well as Thiemann, Nitz and Schmeling mainly results from the different acceleration statuses of the reference populations. Considering the possible discrimination of a defendant, it is necessary to avoid any overestimation of chronological age in criminal proceedings. Compared to the established methods, the method of Gilsanz and Ratib is less suitable for forensic age estimation in criminal proceedings.

The authors consider the possible implementation of corresponding software on various desktops (PC and Mac), laptops and PDAs as an essential innovative criterion of the atlas of skeletal maturity by Gilsanz and Ratib [6]. Computer-based applications are now also available for various other methods of skeletal age assessment. However, the significant gain in independence from usual reference books and study sites remains questionable.

The software provided for the Gilsanz–Ratib method offers a user-friendly interface with simple navigation. An overview image of the complete hand skeleton as well as magnifications of maturation specific anatomic regions were generated for each sex and age standard. However, the deliberate exclusion of complex image-magnifying functions makes a flexible zoom as well as a rotation in images impossible. This makes a quick change clearly more difficult regarding the analysis of the total architecture and concrete morphological structures.

Today, the examiner is more and more frequently confronted with digitised radiographs. Only with the help of appropriate technical conditions that allow these images to be imported to the used device, would a locally flexible analysis be possible. But without simultaneous evaluation of the images, however, the user-friendliness of the programme would be further limited. The connection to a diagnostic centre seems to be desirable for forensic age estimation in criminal proceedings in any case due to the broad spectrum of recommended methods.

In a possible second edition of the digital atlas of skeletal maturity by Gilsanz and Ratib [6], the mix-up in the female radiographic standards for the age groups 24 months and 28 months should be corrected.

Conclusions

1. The accuracy of the established atlas methods of Greulich and Pyle and/or Thiemann, Nitz and Schmeling is comparable to the accuracy of the method of Gilsanz and Ratib.
2. Due to the risk of age overestimation in females, the method of skeletal age assessment of Gilsanz and Ratib only seems to be suitable for forensic age diagnostics to a limited extent.
3. The digital version of the radiographic atlas is not a suitable alternative for forensic age estimation.

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