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ORIGINAL ARTICLE

Applicability of Greulich and Pyle method for age assessment in forensic practice on an Italian sample

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Abstract
Background The main importance in age estimation lies in the assessment of criminal liability and protection of unaccompanied minor immigrants, when their age is unknown. Under Italian law, persons are not criminally responsible before they reach the age of 14. The age of 18 is important when deciding whether juvenile or adult law must be applied. In the case of unaccompanied minors, it is important to assess age in order to establish special protective measures, and correct age estimation may prevent a person over 18 from benefiting from measures reserved for minors.
Objective Since the Greulich and Pyle method is one of the most frequently used in age estimation, the aim of this study was to assess the reproducibility and accuracy of the method on a large Italian sample of teenagers, to ascertain the applicability of the Atlas at the critical age thresholds of 14 and 18 years.
Materials and methods This retrospective study examined posteroanterior X-ray projections of hand and wrist from 484 Italian–Caucasian young people (125 females, 359 males) between 11 and 19 years old. All radiographic images were taken from trauma patients hospitalized in the Azienda Ospedaliero Universitaria Ospedali Riuniti of Ancona (Italy) between 2006 and 2007. Two physicians analyzed all radiographic images separately. The blind method was used.
Results In the case of an estimated age of 14 years old, the true age ranged from 12.2 to 15.9 years (median, 14.3 years, interquartile range, 1.0 years) for males, and 12.6 to 15.7 years (median, 14.2 years, interquartile range, 1.7 years) for females. In the case of an estimated age of 18 years, the true age ranged from 15.6 to 19.7 years (median, 17.7 years, interquartile range, 1.4 years) for males, and from 16.2 to 20.0 years (median, 18.7 years, interquartile range, 1.8 years) for females.
Conclusion Our study shows that although the GPM is a reproducible and repeatable method, there is a wide margin of error in the estimation of chronological age, mainly in the critical estimated ages of 14 and 18 years old in both males and females.

Keywords Forensic age diagnosis · Hand and wrist radiography · Greulich and Pyle method · Age estimation

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Introduction

The main importance in age estimation lies in the assessment of criminal liability and protection of unaccompanied minor immigrants, when their age is unknown. Under Italian law, persons are not criminally responsible before they reach the age of 14. The age of 18 is important when deciding whether juvenile or adult law must be applied. In the case of unaccompanied minors, it is

important to assess age in order to establish special protective measures, and correct age estimation may prevent a person over 18 from benefiting from measures reserved for minors.

Among the updated recommendations of the *Study Group on Forensic Age Diagnostic of the German Association of Forensic Medicine* (AGFAD) [1], X-ray examination of the hand and wrist is one basic step for age estimation. The Greulich and Pyle method (GPM) [2] is one of the most frequently used for evaluation of skeletal age from radiographs. However, this method is based on comparative analysis with a series of standard radiographs collected for clinical purposes in the 1930s, and its true suitability as an age diagnostic tool for forensic purposes is now debatable.

The aim of this study was to assess the reproducibility and accuracy (reliability) of the GPM on a large Italian sample of teenagers, to ascertain the applicability of the Atlas at the critical age thresholds of 14 and 18 years.

Materials and methods

Subjects and materials

This retrospective study examined posteroanterior X-ray projections of hand and wrist from 484 Italian–Caucasian young people (125 females, 359 males) between 11 and 19 years old. All subjects were traumatized patients hospitalized in the Azienda Ospedaliero Universitaria Ospedali Riuniti of Ancona (Italy) between 2006 and 2007. All X-ray projections were obtained with the same X-ray apparatus (technical data of X-ray equipment and settings: FFD 110 cm, no grid, 100 mA, 4 mAs, 50 kV, CR Fuji software, Multifrequency processing). All radiographic images were downloaded from the RIS-PACS (Radiological Information System–Picture Archiving Communication System) and printed on photographic paper by a Xerox Phaser 8560. When necessary, digital images were submitted to contrast enhancement before printing for easier interpretation. X-rays, showing some evidence of bone fracture or soft tissue abnormalities, were discarded. Since this study was based strictly on radiographic images, we had no information about patients' growth disorders or other illnesses.

Two physicians, LM and GF respectively, resident forensic pathologists with 4 years of experience and full-time pediatric radiologists, staff members, analyzed all radiographic images separately. All assessments were carried out according to the GPM. The blind method was used, and only patient gender was known to readers. The age and sex distribution of the sample are shown in Table 1.

Table 1 Sample studied by age and sex

Chronological age (completed years)	Males		Females	
	N	Mean±SD (years)	N	Mean±SD (years)
11	8	11.6±0.2	8	11.6±0.3
12	28	12.4±0.3	19	12.5±0.2
13	34	13.5±0.3	15	13.6±0.3
14	61	14.5±0.3	14	14.5±0.3
15	67	15.4±0.3	17	15.5±0.3
16	48	16.5±0.3	17	16.6±0.4
17	41	17.5±0.3	12	17.5±0.3
18	35	18.5±0.3	9	18.6±0.2
19	37	19.4±0.3	14	19.6±0.2
Total	359		125	

N number of cases, *SD* standard deviation

Statistical analysis

The chronological age (CA) of each subject was calculated as the difference between the date of the X-ray and the declared date of birth. Skeletal age (SA) was used as an estimation of chronological age. In order to test how closely the GPM could predict CA, the estimation error (relative error) was defined as the difference between SA and CA. As the relative error was calculated by subtracting SA from CA, a negative result indicates overestimation, and a positive one underestimation. The accuracy of the GPM was assessed by breaking down the sample by sex and SA subgroup. The median, first (q_1) and third quartiles (q_3), minimum and maximum values of CA were calculated for each SA subgroup. Results are shown in Tables 3 and 4.

For accuracy, we calculated both the mean of relative errors (MRE) and the mean of absolute errors (ME).

To test intraobserver reliability (repeatability), a random sample of 47 radiographic images (8 females, 39 males) were reexamined by the two readers after a 1-month interval. Cohen's Kappa was used to test the reproducibility (interobserver variability) and repeatability (intraobserver variability) of the GPM. The Shapiro–Wilks test was used to verify the normality of the distribution of CA in each skeletal age group. To state the probability of being right in age prediction, we used Čebyšëv's inequality [3] and its descendants, because it allows a lower bound to be placed on the probability that some random variables are equal to or more than a set value, given only the mean and the variance of that variable. No other information about that variable's distribution is required.

Statistical analysis was carried out by the R statistical program [R Development Core Team] (2008). (R: A language and environment for statistical computing. R

Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org). The threshold of significance was set at 5%.

Results

Repeatability and reproducibility

When the results of the observers were considered separately in 49.8% (GF) and 57.4% (LM) of reexamined radiographs, the assessments were the same. In 12.8% (GF) and 0.0% (LM), the differences between the first and second assessments were more than 1 year. As regards to reproducibility in 57.3% of all the analyzed radiographic images, there was a full agreement between the two readers' estimations. In 10.3%, the two estimated skeletal ages differed by 6 months. The two observers disagreed by more than 1 year in 6.6%. Cohen's Kappa test demonstrated no statistically significant intra- or interobserver differences in the age estimation performed by the two readers (Table 2).

As regards the distribution of errors and their absolute values, the following results were achieved.

LM: For males, the mean relative error (MRE)±standard error (se) was −0.20±0.04 years, and the mean of absolute values, ME±se was 0.66±0.03 years. For females, MRE was 0.09±0.08 (ME=0.72±0.05 years). For 79.4% of males and 73.0% of females, the difference between CA and SA was less than or equal to 1 year.

GF: For males, the mean relative error (MRE)±standard error (se) between SA and CA was -0.17±0.05 years (ME=0.69±0.03 year). For females, the MRE±se was −0.23±0.1 (ME=0.91±0.06 years). For 76.3% of males and 60.3% of females, the difference between CA and SA was less than or equal to 1 year.

Reliability and suitability

The following statistical analyses were carried out on age estimations only performed by LM, since we were interested in age estimation reliability when GPM is used by forensic pathologists, and no significant differences were found between the two readers.

Table 2 Cohen's Kappa values and their 95% confidence intervals (95% CI) used to evaluate reproducibility and repeatability of GPM

Repeatability		Reproducibility
Forensic pathologist (LM)	Radiologist (GF)	
0.943 (0.866–0.969)	0.870 (0.773–0.928)	0.949 (0.938–0.957)

The Shapiro–Wilks test showed that the CA cohort distribution was not always normal for each estimated age. In detail, for an estimated age of 16 years, the test value was W=0.93. This allows the null hypothesis of normality of CA distribution to be rejected (p=0.03).

Considering the Shapiro–Wilks test results (no normal distribution) and the skewness of the CA distribution for a given estimated age, CA distributions are represented in median values, upper and lower quartiles, and minimum and maximum observed values. All data are shown in Tables 3 and 4 for males and females, respectively.

Because of the skew distributions, the median was used to represent the measure of central tendency, and interquartile range was considered as a robust measure of statistical dispersion of error of the estimated ages. In our sample of children, median values of error varied from −0.6 to 0.5 years for males and from −0.7 to 0.7 for females. As the gap between estimated and real ages was calculated as difference between CA and SA, negative values indicate overestimation, and positive ones, underestimation. The interquartile range varied from 0.2 to 1.4 years for males and from 0.3 to 1.7 years for females.

Considering the two critical age thresholds of 14 and 18 years old, to state the probability that a subject is almost 14 or 18 years old using GPM, Čebyšëv's inequalities were calculated, and remaining sound for variables of arbitrary distribution, exactly fit any age distribution.

The results of Čebyšëv's inequalities are shown in Tables 5 and 6 for males and females, respectively. For some SA groups, it was not possible to state a minimum probability value, or the found value was not statistically significant.

Table 3 Distribution of CA for each SA group according to GPM

Males						
SA	N	Min	FQ	Median	TQ	Max
11.5	10	11.3	11.7	12.0	12.2	12.6
12.5	16	11.7	12.1	12.7	13.1	13.4
13	14	11.3	12.4	12.5	12.6	13.2
13.5	13	11.5	13.4	13.6	14.1	14.5
14	59	12.2	13.8	14.3	14.8	15.9
15	22	13.8	14.9	15.1	15.5	16.3
15.5	16	14.0	14.7	15.0	15.2	16.7
16	60	14.4	15.1	15.4	16.0	17.6
17	35	14.9	16.4	16.7	17.0	17.8
18	29	15.6	16.8	17.7	18.2	19.7
19	85	16.1	18.0	18.8	19.3	19.9

SA skeletal ages, *N* number of cases, *Min* minimum age, *Max* maximum age, *FQ* first quartile, *TQ* third quartile

Table 4 Distribution of CA for each SA group according to GPM

Females						
SA	n	Min	FQ	Median	TQ	Max
11	4	11.2	11.2	11.4	11.5	11.6
12	15	11.5	12.0	12.2	12.5	13.8
13	12	12.3	12.7	13.0	13.4	14.5
13.5	4	12.4	12.5	12.8	13.2	13.6
14	6	12.6	13.6	14.2	15.2	15.7
15	20	13.3	14.0	14.5	15.0	15.6
16	22	14.5	15.3	16.0	16.8	18.4
17	7	15.7	16.4	16.8	17.0	17.2
18	35	16.2	17.7	18.7	19.5	20.0

SA skeletal ages, *N* number of cases, *Min* minimum age, *Max* maximum age, *FQ* first quartile, *TQ* third quartile

We summarized and simplified all the results from a forensic point of view: assuming that the SA of 18 years was used as a threshold value to predict reaching adult age, we overestimated 22.9% of 16- and 73.2% of 17-year-old boys. In girls, 23.5% of 16- and 75.0% of 17-year-old girls were overestimated. No boys and only one girl were underestimated. When we used the SA of 14 years as the threshold for reaching the age of 14, 7.1% of 12-year-old and 58.8% of 13-year-old boys were overestimated; 8.2% of 14-year-old boys were underestimated. At the same time, 5.3% of 12-year-old and 46.7% of 13-year-old girls were overestimated; and 7.1% of 14-year-old girls were underestimated. All data (absolute values) are shown on Tables 7, 8, 9, and 10 for the male and female samples.

Table 5 Probability of correctness in age estimation in age thresholds of 14 and 18 years

Males							
SA	N	mCA	SD	CA≤14	CA≥14	CA≤18	CA≥18
11.5	10	12.0	0.4	96.2%		99.6%	
12.5	16	12.6	0.6	83.8%		98.9%	
13	14	12.5	0.4	91.7%		99.4%	
13.5	13	13.6	0.8			96.7%	
14	59	14.3	0.8			95.4%	
15	22	15.1	0.7		71.6%	94.5%	
15.5	16	15.0	0.6		71.6%	95.4%	
16	60	15.6	0.7		82.4%	91.5%	
17	35	16.7	0.6		94.7%	77.5%	
18	29	17.6	1.0		93.2%		85.6%
19	85	18.6	0.9		96.5%		

SA skeletal ages, *N* number of cases, *mCA* mean chronological age for each SA group

Table 6 Probability of correctness in age estimation in age thresholds of 14 and 18 years

Females							
SA	N	mCA	SD	CA≤14	CA≥14	CA≤18	CA≥18
11	4	11.4	0.2	99.4%		99.9%	
12	15	12.3	0.5	90.6%		99.1%	
13	12	13.1	0.6	55.9%		98.5%	
13,5	4	12.9	0.5	75.8%		98.9%	
14	6	14.3	1.2			89.2%	
15	20	14.5	0.6		41.8%	96.6%	
16	22	16.0	0.9		83.0%	78.3%	
17	7	16.7	0.6		95.6%	81.8%	
18	35	18.5	1.1		94.5%		

SA skeletal ages, *N* number of cases, *mCA* mean chronological age for each SA group

Discussion

The GPM was developed and used to assess skeletal age in children and young people. As skeletal maturation may be considered an index of biological age, the GPM is a useful tool for evaluating the normal development of young people. However, since it was developed for clinical practice, and its reference standards were built on a large number of a White American population living in the 1930s, the question now arises as to how suitable it really is as a diagnostic tool for age (converting a biological parameter into a chronological one) for forensic purposes, and how this procedure could stand up in court. In addition, the main problems in the use of this method for forensic purposes lie in the significantly different ossification rates among individuals of the same and different populations [2, 4–15], depending on various factors: genetics, diseases, socioeconomic status, and modernization in medicine [16–21], as well as on the reliability of measurement of SA when different technical standards are used [22]. The last problem with the GPM is that the maximum skeletal age that can be evaluated is 19 years for males and 18 for females. These limitations and the difficulty of interpreting

Table 7 Frequency of under- and overestimated males in reaching adult age

Chronological age (completed years)	Estimated as minor	Estimated as adult	N
15	66	1	67
16	37	11	48
17	11	30	41
18	0	35	35
19	0	37	37

Table 8 Frequency of under- and overestimated males in reaching 14 years old

Chronological age (completed years)	Estimated as minor of 14 years old	Estimated as equal or over 14 years old	N
12	26	2	28
13	14	20	34
14	5	56	61
15	0	67	67
16	0	48	48

Table 10 Frequency of under- and overestimated females in reaching 14 years old

Chronological age (completed years)	Estimated as minor of 14 years old	Estimated as equal or over 14 years old	N
12	18	1	19
13	8	7	15
14	1	13	14
15	0	17	17
16	0	17	17

X-rays of an almost ossified hand raise doubts about the reliability of the method, when it is used to predict reaching legal adult age.

Despite these limitations in accordance with previous studies [10, 11, 14, 23–27], our results showed that the GPM is a reproducible and repeatable method. This means that although it closely depends on the judgment of the person interpreting it, there is a high level of agreement between different readers in assessment of skeletal age. We also found that the method can be easily learnt and performed even by an initially inexpert user. This is a great advantage in terms of time.

Regarding the reliability, precision, and accuracy of the GPM, we found that it is not consistent when used to assess CA for legal purposes. The true ages of subjects in some skeletal age subgroups were overestimated and others underestimated. It was also imprecise because of statistical dispersion of error estimation (see Tables 3 and 4).

As regards the aim of this study, great error variability was found in the critical estimated ages of 14 and 18 years old in both males and females. In the case of an estimated age of 14 years old, true ages ranged from approximately 12 to 16, and in the case of an estimated age of 18 years, true ages ranged from nearly 16 to 20 years, with slight gender variations (Tables 3 and 4).

These results highlight the problem of evaluating a safe range for age estimation. In our study, the range encompassing all observations (minimum and maximum CA values) vary from 0.4 to 4.1 years and 50% of the observations (interquartile range) ranged from 0.2 to 1.8 years. This conservative approach was suggested by the updated recommendations of the AGFAD to state the most probable age, describing the reference standard used and the most likely minimum and maximum age of the subject under investigation, together with the probability that the evaluated chronological age is correct. As we demonstrate that chronological age distribution for a given estimated age is neither normal nor symmetric, the average value of ±1.96 standard deviation is not suitable for stating a range of 95% probability regarding CA. For these reasons, to check the correctness of our estimated ages, we applied Čebyšëv's inequalities, which are useful in cases of unknown distribution of CA. The strength of our statement about an age of less than 18 years evaluated by this method decreases progressively when an SA of 18 is approached, up to a minimum of 77.5 at 17 years for males (78.3% at 16 for females) (Tables 5 and 6). Lastly, the worst results were obtained when GPM was tested to predict the achievement of adult age, due to the lack of standards in the Atlas for this age.

Table 9 Frequency of under- and overestimated females in reaching adult age

Chronological age (completed years)	Estimated as minor	Estimated as adult	N
15	17	0	17
16	13	4	17
17	3	9	12
18	1	8	9
19	0	14	14

In conclusion, our study shows that although the GPM is a reproducible and repeatable method, (1) there is a wide margin of error in the estimation of chronological age; (2) there is great variability of error in the critical estimated ages of 14 and 18 years old in both males and females; (3) chronological age is unpredictable, with a high degree of probability, when full ossification has occurred.

It is plausible to assume that the main sources of errors in age estimation with the GPM lie in the biological variability of skeletal development and the inadequacy of the Atlas standards. A new set of standards, more suitable for modern populations, would be of great help in this respect. The use of other age diagnostic methods may also help to reduce the margin of error in age diagnosis. Some authors [23, 28] have shown that the combination of two chronological age prediction factors (assessment) can lead to a significant increase in the efficacy of the prediction that a subject is under the 18-year-old age limit or not. Also, as regards proving that an individual has reached the age of 18 years, important tools for forensic purposes are

evaluation of the ossification status of the medial clavicular epiphysis [29, 30] and the study of third molar development [31, 32].

We believe that extensive studies are needed to confirm that the combined analysis of several biological parameters (anthropometric, physical, dental, skeletal, etc.) can reduce the margin of error with respect to a single analysis.

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