Original Article

Age estimation by assessing developmental stages of the distal end of radius bone in Thai population

Phonkit Sinpitaksakul, D.D.S., Grad. Dip. Clin.
Sunpatch Benjavongkulchai, D.D.S., M.Sc.
Anansit Jinawong, D.D.S.
Chawanat Wongpattaraworrakul, D.D.S.
Sirapat Pipattanachat, D.D.S.
Pisha Pittayapat, D.D.S., M.Sc., Ph.D.

Department of Radiology, Faculty of Dentistry, Chulalongkorn University, Bangkok, Thailand

Abstract

Objective: The aim of this study was to evaluate developmental stages of the radius bone and compare it with the chronological age of Thai population.

Methods: Three hundred hand and wrist radiographs (150 males, 150 females) of subjects (age 7-20 years) were retrospectively collected. The developmental stages of the distal end of the radius bone were modified from Tanner-Whitehouse 3 and categorized into 4 stages: 1) non-capping, 2) capping, 3) partial fusion and 4) complete fusion. Each radiograph was scored by 3 observers. Sixty subjects were re-evaluated for intra- and inter-observer agreement. Statistical analysis was performed.

Results: The mean ages of each stage were presented: stage 1, 10.63 ± 1.52 years in males and 9.54 ± 1.08 years in females; stage 2, 13.83 ± 1.15 years in males and 12.06 ± 1.28 years in females; stage 3, 15.39 ± 0.74 years in males and 14.18 ± 1.22 years in females; stage 4, 17.57 ± 1.45 years in males and 17.04 ± 1.56 in females. Statistically significant differences were found between ages of males and females in stage 1, 2 and 3. Distribution of data showed that all subjects with partially fused radius bone were younger than 18. However, subjects presented with completely fused radius bone could be at least 15 years old. Additionally, when the subject's known age was 18 years old or older, complete fusion of the radius bone could be observed.

Conclusion: Radius bone developmental staging is a potential predictor for age estimation of legal cases in Thai population. Further studies with increased number of subjects will be of benefit.

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Keywords: Age estimation, Hand and wrist radiography, Radius, Thai

Correspondence: Pisha Pittayapat, p. pittayapat@gmail.com

Introduction

Age estimation plays an important role in immigration and human trafficking. It can offer helpful information in human identification and legal cases (Aggrawal, 2009, Black and Ferguson, 2016, Franklin et al., 2015, Sharma, 2007, Smith and Brownlees, 2011). Recently, illegal immigration and human trafficking are national problems in Thailand. Government policy is aiming to deal with these issues by the help of law enforcement. By identifying the age of the victims or immigrants, legal procedure can then be processed. There are several crucial legal ages regarding Thai laws; 10, 13, 15, 18, and 20 years old. These ages may determine the fate of both victims and defendants (Thailand, Criminal code, Sections 73-79, 282-287).

Age estimation can be done using dental and skeletal assessment. Skeletal age estimation method is useful for children and adolescents. Age estimation of several bones, such as clavicles, hand bones, ulna bone, and radius bone, can be achieved. The hand and wrist age estimation using hand and wrist radiograph is widely used because it is easy and cost-effective and the radiation dose to the young individuals is rather minimal. Evaluation of developmental stages and epiphyseal ossification of the hand and wrist bone is done on the radiograph (Black and Ferguson, 2016, Franklin et al., 2015, Satoh, 2015, Smith and Brownlees, 2011).

Several hand and wrist age estimation methods were previously studied and published (Eklöf and Ringertz, 1967, Fishman, 1982, Gilsanz and Ratib, 2005, Greulich and Pyle, 1959, Tanner et al., 2001). These methods involved a comparison between the radiograph and a radiographic atlas, calculations of the age from developmental stages of each bone and observations of the presence or absence of specific developmental features of the bones in the region (Fishman, 1982, Greulich and Pyle, 1959, Tanner et al., 2001).

Radius bone is one of the two bones in the forearm. This bone can be visualized on the typical hand and wrist radiograph. The distal epiphysis of radius is usually completely ossified during the age of 17-20 years old (Greulich and Pyle, 1959, Buikstra and Ubelaker, 1994, Byers, 2005, Baumann, 2009). This age range is very important in legal and jurisdictional procedure in Thailand (Thailand, Criminal code, Sections 73-79, 282-287).

Several researchers studied the association between the chronological age and the ossification stage of the distal radius bone (Baumann et al., 2009, Hassan et al., 2016, Patel et al., 2011) but literature review did not show any studies on Thai population. Ethnicity is one of the factors influencing skeletal maturity, thus may influence the results of age estimation (Black and Ferguson, 2016, Franklin et al., 2015, Manzoor Mughal et al., 2014, Smith and Brownlees, 2011). Therefore, the aims of this study were to evaluate developmental stages of the distal end of the radius bone and compare it with the chronological age of Thai children and adolescents.

Material and methods

Samples

The study protocol was approved by the Ethical Committee (032/2016 study no. 2016-002).

The sample size was calculated based on results of a previous published study by Baumann et al., 2009 as shown on equation 1:

$$n = \frac{z^2_{1-\frac{\alpha}{2}}\sigma^2}{d^2}$$

Equation 1 Sample size calculation formula for testing population means (Daniel, 1995)

SD. (α) = 1.5

Error (d) = 1

α = 0.05

n = 9

At least 9 females and 9 males were collected for each developmental stage.

Three hundred digital hand and wrist radiographs of subjects (150 males, 150 females, age 7-20 years, mean 12.33 years, standard deviation (SD) 2.68 years) taken at the Radiology clinic, Faculty of Dentistry, Chulalongkorn University, Bangkok, Thailand from 2010-2016 were retrospectively collected (Table 1). The selection criteria were as follows:

- All patients were presented with Thai nationality in the dental chart.

- The chronological age of the subjects was between 7-20 years old on the X-ray date.

- All patients did not have any systemic diseases that might affect skeletal development and maturity.

The radiographic machine used was Carestream™ CS 8000c or CS 9000c radiographic machine (Carestream Health, Inc., Rochester, NY, USA). The exposure parameters were set according to the patients' size. All images were stored in the hospital picture archiving and communication system (PACS) (Infinitt® Healthcare Co., Ltd., Seoul, South Korea). Radiographs of both left and right hand and wrist were used in this study as no significant difference between left and right side was previously reported (Greulich and Pyle, 1959, Baer and Djrkatz, 1957, Hackman and Black, 2012).

Developmental stages and observation

The developmental stages of the distal end of the radius bone, as shown in Table 2, were modified from the classifications of Tanner-Whitehouse 3 and Baumann et al. (Tanner et al., 2001, Baumann et al., 2009).

All samples were randomized. Three observers: one master student in dentomaxillofacial radiology, one dentomaxillofacial radiologist with 12 years-experience and one dentomaxillofacial radiologist with 15 years-experience, were pre-calibrated before starting the observation. Radiographs were shown to the observers on PACS Infinitt® software (Infinitt® Healthcare Co., Ltd., Seoul, South Korea). During the observation, the observers were blinded from the subjects' chronological age. Developmental stages of the distal end of radius bone were given to each radiograph by each observer independently. The stage given by at least two observers was chosen as a representative stage for each radiograph. Sixty radiographs were randomly selected for a repeated observation which was done 4 weeks after the first observation by the first observer.

Statistical analysis

Descriptive analysis was done. The mean age and standard deviation (SD) of each developmental stage of the distal end of radius was calculated. Shapiro-Wilk test was used to analyze the data distribution. Mann-Whitney U test was performed to compare the age of each developmental stage between males and females. Kruskal-Wallis with a post-hoc Dunn-Bonferroni test was performed to compare the age of all developmental stages. In addition, Spearman's correlation test was performed to find whether there is any correlation between developmental stages of the distal end of the radius bone and the chronological ages. The significant level was set at $p < 0.05$.

Results

Three hundred hand and wrist radiographs of Thai children and adolescents were evaluated in this study. Developmental stages of the distal end of the radius bone were scored. Distributions of subjects, males and females, in stage 1-4 are shown on Figure 1.

The distribution of data showed that 100% of female and 92.4% of male subjects with stage 1 (non-capping) were younger than 13 years old. 97.9%

of females and 87.5% of males with stage 2 (capping) were younger than 15 years old. All subjects with stage 3 (partial fusion) were younger than 18 years old. It was also established that subjects who were presented with stage 4 (complete fusion) were at least 15 years old. Finally, all subjects with age at least 18 years old were presented with stage 4 development. Overlapping of stage 3 and stage 4 was found between 15-18 years old.

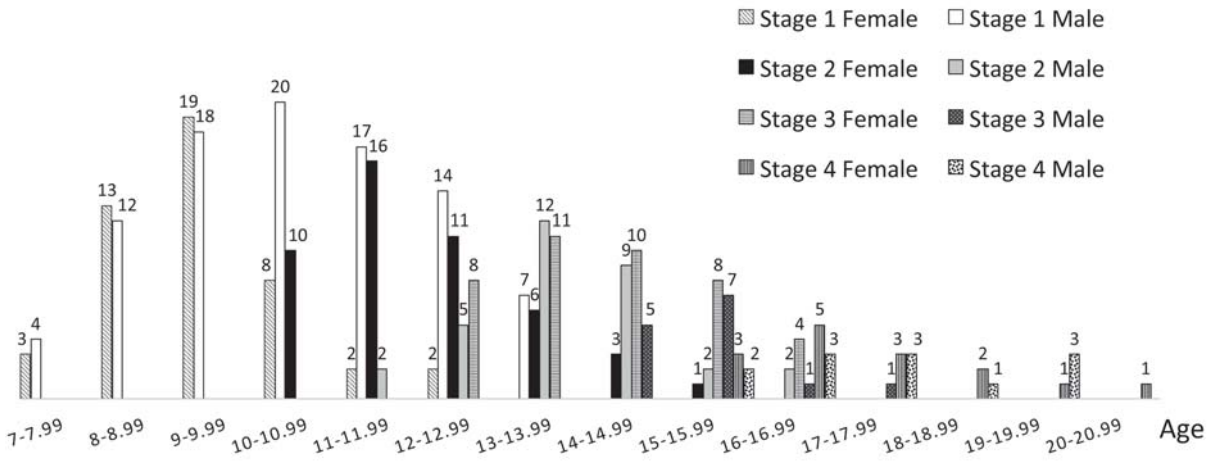

Figure 1: A column graph showing distribution of subjects, males and females, with different developmental stages, in each age range from 7-20.99 years old. The numbers at the top of the columns are number of subjects.

Table 1: Distribution of subjects in each age group with mean age ± standard deviation.

Age group	Female		Male	
	n	Mean age (year)	n	Mean age (year)
7-7.99	3	7.47 ± 0.45	4	7.59 ± 0.10
8-8.99	13	8.59 ± 0.28	12	8.64 ± 0.29
9-9.99	19	9.70 ± 0.27	18	9.63 ± 0.19
10-10.99	18	10.51 ± 0.30	20	10.49 ± 0.30
11-11.99	18	11.52 ± 0.30	19	11.58 ± 0.33
12-12.99	21	12.44 ± 0.29	19	12.38 ± 0.31
13-13.99	17	13.45 ± 0.18	19	13.40 ± 0.29
14-14.99	13	14.44 ± 0.36	14	14.59 ± 0.31
15-15.99	12	15.38 ± 0.28	11	15.52 ± 0.37
16-16.99	9	16.22 ± 0.22	6	16.48 ± 0.30
17-17.99	3	17.66 ± 0.42	4	17.36 ± 0.25
18-18.99	2	18.31 ± 0.01	1	18.84*
19-19.99	1	19.49*	3	19.46 ± 0.28
20-20.99	1	20.15*	0	-

*only one subject in the age group

Table 2: Definitions of developmental stages of the distal end of radius bone modified from Tanner-Whitehouse 3 and Baumann et al. (Tanner et al., 2001, Baumann et al., 2009).

Developmental stage	Definitions	Radiographic examples
1	Non-capping - Epiphysis entirely separates from diaphysis. - Lateral margins of epiphysis do not project toward diaphysis.	
2	Capping - Epiphysis entirely separates from diaphysis - Lateral margins of epiphysis project toward diaphysis.	
3	Partial fusion - The space between epiphysis and diaphysis is partially visible.	
4	Complete fusion - Both epiphysis and diaphysis are completely joined. - White line (physeal scar) between epiphysis and diaphysis may be visible.	

Table 3: Descriptive data and comparison between males and females within each stage.

Stage	Female		Male		Mean difference	Mann-Whitney U test (p-value)
	n	Mean age ± SD	n	Mean age ± SD		
1	47	9.54 ± 1.08	92	10.63 ± 1.52	1.09	< 0.001
2	47	12.06 ± 1.28	32	13.83 ± 1.15	1.77	< 0.001
3	41	14.18 ± 1.22	14	15.39 ± 0.74	1.21	0.002
4	15	17.04 ± 1.56	12	17.57 ± 1.45	0.53	0.393

Comparisons between males and females were done within each stage by Mann-Whitney U test. Statistically significant differences were found between males and females in stage 1, 2 and 3. Descriptive data and results of Mann-Whitney U test are reported in Table 3.

Comparison of age between all developmental stages by Kruskal-Wallis test showed significant differences ($p < 0.001$) for both males and females. The post-hoc Dunn-Bonferroni test showed significant differences between all pairs of females, except between stage 3 and 4. On the other hand, only stage 1 was significantly different from other stages for males.

Spearman's correlation test showed significant association between chronological age and radius bone staging in both males and females ($p < 0.001$).

Intra- and inter-observer agreement

Results of Kappa statistics showed substantial to almost perfect agreement for both inter-observer (k = 0.79-0.86) and intra-observer agreement (k = 0.86).

Discussion

This study compared the developmental stages of the distal end of radius bone with the chronological age of Thai children and adolescents.

Several age estimation methods, both dental and skeletal assessment, are useful in estimating the age of individuals (Demirjian et al., 1973, Fishman, 1982, Greulich and Pyle, 1959, Kvaal et al., 1995, Tanner et al., 2001). Hand and wrist radiographic assessment was chosen to be studied because it is easy to acquire and not expensive. The radiographs were available in the Faculty of Dentistry where the orthodontic department referred patients to have hand and wrist radiographs for growth evaluation.

In this study, the developmental stages were modified from Tanner-Whitehouse 3 publication (Tanner et al., 2001) and Baumann et al (Baumann et al., 2009). In Tanner-Whitehouse 3, several bones in the hand and wrist region were evaluated and scored for age estimation; however, this method required a lot of time for one case. Thus, only the radius bone was chosen to be studied. Another reason was that the distal end of the radius is the last bone to be ossified in the region (Greulich and Pyle, 1959, Buikstra and Ubelaker, 1994, Byers, 2005, Baumann et al., 2009). Its development takes place during child and adolescence period which is critical in many legal cases (Thailand, Criminal code, Sections 73-79, 282-287). In addition, radius is easy to be visualized and evaluated.

In the original Tanner-Whitehouse 3 classification, the stages of the distal end of the radius bone were categorized into 8 stages from B (just visible ossification center) to I (beginning fusion of the distal end of radius bone). No complete fusion of the epiphysis was mentioned in the original Tanner-Whitehouse 3 (Tanner et al., 2001).

Baumann et al., defined the developmental stages of the distal end of radius bone into 5 stages: 1: epiphysis not ossified, 2: epiphysis ossified without any fusion, 3: partial fusion, 4: complete fusion with visible physeal scar, 5: complete fusion without physeal scar (Baumann et al., 2009).

Stage 1 of Baumann et al. classification was not included because the subjects would surely be younger than the samples collected in this study. Therefore, in the present study, stage 1, non-capping, was referred to stage B-G as mentioned in Tanner-Whitehouse 3 and stage 2 of Baumann et al. classification (Tanner et al., 2001, Baumann et al., 2009). The reason that Tanner-Whitehouse 3 staging was simplified was to reduce any possible errors and confusion of the observers. Additionally, the study would require more samples to be able to define the differences between ages of each developmental stage. Stage 2, capping, was referred to stage 2 of Baumann et al. as the authors did not give an interest to the capping morphology of the epiphysis, and stage H of Tanner-Whitehouse 3, which was the stage before the last stage (Tanner et al., 2001, Baumann et al., 2009). Stage 3, partial fusion, was similar to stage 3 of Baumann et al. and similar to stage I of Tanner-Whitehouse 3 (Tanner et al., 2001, Baumann et al., 2009). Stage 4, complete fusion regardless of the epiphyseal scar, was referred to stage 4 and 5 of Baumann et al. because the scar can remain visible throughout life and may not be a reliable indicator for age estimation (Tanner et al., 2001, Davies et al., 2015).

Very good intra- and inter-observer agreement was found. This assured that the observational method was reliable and can be reproduced. A calibration session was done prior to the observation to calibrate the standard of all observers.

The findings of this study confirmed the difference in skeletal maturity between males and females. Significant differences were found between males and females from stage 1, 2 and 3. The mean age showed that females had more advanced radius bone development than males, predominantly in earlier stages (Table 3). No significant difference was found between males and females in stage 4 as the development was completed.

Several researchers have studied the developmental stages of the distal end of the radius bone (Baumann et al., 2009, Greulich and Pyle, 1959, Hassan et al., 2016, Schmidt et al., 2013). The Greulich and Pyle Radiographic Atlas of the hand and wrist presented the stages of bone development in the hand and wrist region including the radius bone of males and females. For the radius bone, the atlas showed the age of capping stage at 14 years old for males and 12 years old for females which were similar to the findings of this study. On the other hand, the partial fusion stage was presented at 18 years old for males and 15 years old for females in the atlas which were later when compared to the present study (Greulich and Pyle, 1959). The differences may be influenced from the difference in ethnicities of the subjects (Buken et al., 2007, Zhang et al., 2009, Zafar et al., 2010). Another reason may be the difference in generations of the subjects.

There were published evidences of the influence of population generations on growth and development of children (Hawley et al., 2009, Hsieh et al., 2013). Hawley et al. evaluated skeletal maturation of South African children between 1962 and 2001 using Greulich and Pyle and found significant secular increases in skeletal maturity (Hawley et al., 2009). The findings were supported by another study by Hsieh et al. The authors reported that the secular trend of skeletal maturation of children in the mid-2000s was faster than that in the mid-1960s when evaluated the hand and wrist bones using Tanner-Whitehouse 3 method (Hsieh et al., 2013). Regarding Thai criminal law, the youngest legal age is 10 years old; therefore, subjects aged 7-9 years old were included in this study to cover young age groups potentially affected by advanced

skeletal maturation. Additionally, the capping of radius bone epiphysis was reported as around 12 years old in females (Greulich and Pyle, 1959) and secularly advanced maturation was previously stated, subjects with stage 2 in this study potentially covered subjects as young as 10 years old. Therefore, the inclusion of subjects younger than 10 years would better represent the developmental stages of the distal end of radius bone.

Baumann and colleagues studied stages of the radius and ulna bone ossification in German subjects whose age ranged from 10-30 years (Baumann et al., 2009). The developmental stages included: 1, epiphysis not ossified; 2, epiphysis ossified; 3, partial union of the epiphysis and metaphysis; 4, complete union of the epiphysis and metaphysis, epiphyseal scar visible; 5, complete union of the epiphysis and metaphysis, epiphyseal scar non-discernable. Focusing at stage 3 and 4, which were similarly defined with our study, their results showed that the mean age of stage 3 was younger than the findings in this study for both males and females. However, the mean age of stage 4 was older than the results in this study for both sexes. This might result from differences of the subjects' age range, ethnicities and growth rate as the age gap between stage 3 and 4 in their study was much wider than in the present study (Baumann et al., 2009).

Hassan et al. published a study in 2016 (Hassan et al., 2016). The study aimed to evaluate the developmental stages of the distal end of the radius bone in Kashmiri population, age 12-20 years old. Direct comparison between their results and the results of the present study was not possible due to a difference in developmental staging categories. Hassan et al. reported that the complete fusion of the distal end of the radius in 100% males was observed at 18-19 years and at 17-18 years in 100% females. Despite the difference, the same findings with our study was found that skeletal maturation of females were more advanced than males (Hassan et al., 2016).

Another study on the fusion of the radius bone was published by Schmidt et al. (Schmidt et al., 2013). The authors used the ultrasonography to evaluate the ossification stages of the distal end of the radius bone. It was not possible to compare the results between this study and the present study due to differences in methodology and techniques. Nonetheless, the study was interesting as it minimized the used of radiation on living subjects (Schmidt et al., 2013).

Related to Thai law, the critical legal ages that may influence jurisdictional penalties were 10, 13, 15, 18 and 20 years old (Thailand, Criminal code, Sections 73-79, 282-287). The findings of this study were very useful for forensic applications especially for the illegal labor and human trafficking in Thailand. In practice, proper age estimation should consist of various aspects including physical examination, skeletal assessment and dental evaluation.

In this study, the samples were equally divided between males and females. The age of the subjects ranged from 7-20 years old but the number of subjects who were older than 16 years old was rather limited. Subjects with age at least 16 years old are necessary to help determining the completion of the epiphyseal fusion of the radius bone which is crucial for assessing the legal age of 18 years old. Further studies with increased number of samples and possibly a multicenter research to create a national database will be of benefits to Thai society.

Conclusions

Developmental stages of the distal end of the radius bone were evaluated and compared with the chronological age of Thai children and adolescents in this study. It was established that all subjects with partially fused distal end of radius bone were younger than 18 years old. However, subjects presented with

completely fused radius bone could be at least 15 years old. Additionally, when the subjects known age were 18 years old or older, complete fusion of the radius bone could be observed and possibly expected. This research has provided useful information that can assist age estimation of Thai population.

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Conflict of interest

The authors declared that there is no conflict of interest.

References

Aggrawal A. Estimation of age in the living: in matters civil and criminal. J Anat. 2009:1-17.

Baer MJ, Djrkatz J. Bilateral asymmetry in skeletal maturation of the hand and wrist: a roentgenographic analysis. Am J Phys Anthropol. 1957;15:181-96.

Baumann U, Schulz R, Reisinger W, Heinecke A, Schmeling A, Schmidt S. Reference study on the time frame for ossification of the distal radius and ulnar epiphyses on the hand radiograph. Forensic Sci Int. 2009;191:15-8.

Black S, Ferguson E. Forensic anthropology: 2000 to 2010. Boca Raton, FL: CRC Press; 2016.

Buikstra JE, Ubelaker DH. Standards for data collection from human skeletal remains. Fayetteville, AR: Arkansas Archeological Survey Research Series 44; 1994.

Buken B, Safak AA, Yazici B, Buken E, Mayda AS. Is the assessment of bone age by the Greulich-Pyle method reliable at forensic age estimation for Turkish children? Forensic Sci Int. 2007;173:146-53.

Byers S. Introduction to forensic anthropology. 2 ed. London, UK: Pearson Education; 2005.

Daniel WW. Biostatistics: A foundation of analysis in the health sciences. 6 ed. Hoboken, NJ: John Wiley & Sons, Inc.; 1995.

Davies C, Hackman L, Black S. The epiphyseal scar: changing perceptions in relation to skeletal age estimation. Ann Hum Biol. 2015;42:348-57.

Demirjian A, Goldstein H, Tanner JM. A new system of dental age assessment. Hum Biol. 1973;45:211-27.

Eklöf O, Ringertz H, editors. A method for assessment of skeletal maturity. Ann Radiol; 1967.

Fishman LS. Radiographic evaluation of skeletal maturation. A clinically oriented method based on hand-wrist films. Angle Orthod. 1982;52:88-112.

Franklin D, Flavel A, Noble J, Swift L, Karkhanis S. Forensic age estimation in living individuals: methodological considerations in the context of medico-legal practice. Res Rep Forensic Med Sci. 2015;5:53-66.

Gilsanz V, Ratib O. Hand bone age: a digital atlas of skeletal maturity. Berlin, Germany: Springer Science & Business Media; 2005.

Greulich WW, Pyle SI. Radiographic atlas of skeletal development of the hand and wrist. Stanford, CA: Stanford University Press; 1959.

Hackman L, Black S. Does mirror imaging a radiograph affect reliability of age assessment using the Greulich and Pyle atlas? J Forensic Sci. 2012;57:1276-80.

Hassan N, Noor F, Ahmad S, Fazili KM. Age of fusion of the distal radial and ulnar epiphyses from hand radiographs-A study in Kashmiri population. Sci Justice. 2016;56:431-6.

Hawley NL, Rousham EK, Norris SA, Pettifor JM, Cameron N. Secular trends in skeletal maturity in South Africa: 1962-2001. Ann Hum Biol. 2009;36:584-94.

Hsieh CW, Liu TC, Jong TL, Tiu CM. Long-term secular trend of skeletal maturation of Taiwanese children between agricultural (1960s) and contemporary (after 2000s) generations using the Tanner-Whitehouse 3 (TW3) method. J Pediatr Endocr Met. 2013;26:231-7.

Kvaal SI, Kolltveit KM, Thomsen IO, Solheim T. Age estimation of adults from dental radiographs. Forensic Sci Int. 1995;74:175-85.

Manzoor Mughal A, Hassan N, Ahmed A. Bone age assessment methods: a critical review. Pak J Med Sci. 2014;30:211-5.

Patel DS, Agarwal H, Shah JV. Epiphyseal fusion at lower end of radius and ulna valuable tool for age determination. J Indian Acad Forensic Med. 2011; 33:125-9.

Satoh M. Bone age: assessment methods and clinical applications. Clin Pediatr Endocrinol. 2015;24: 143-52.

Schmidt S, Schiborr M, Pfeiffer H, Schmeling A, Schulz R. Age dependence of epiphyseal ossification of the distal radius in ultrasound diagnostics. Int J Legal Med. 2013;127:831-8.

Sharma RK. Concise textbook of forensic medicine & toxicology. New Delhi, India: Elsevier India Pvt. Limited; 2007.

Smith T, Brownlees L. Age assessment practices: a literature review & annotated bibliography. New York, NY: Child Protection Section, United Nations Children's Fund; 2011. p. 1-78.

Tanner J, Healy M, Goldstein H, Cameron N. Assessment of skeletal maturity and prediction of adult height (TW3). London, UK: WB Saunders; 2001.

Thailand, Criminal code: Minor Liability. Sections 73-79.

Thailand, Criminal code: Indecency Prostitution. Sections 282-287.

Zafar AM, Nadeem N, Husen Y, Ahmad MN. An appraisal of Greulich-Pyle Atlas for skeletal age assessment in Pakistan. J Pak Med Assoc. 2010;60:552-5.

Zhang A, Sayre JW, Vachon L, Liu BJ, Huang HK. Racial differences in growth patterns of children assessed on the basis of bone age. Radiology. 2009;250:228-35.