Original Article

# Skeletal Age Estimation in A Group of Contemporary Thai Children and Adolescents using Tanner-Whitehouse 3 (TW3) Method

**Sunpatch Benjavongkulchai**[1] **and Pisha Pittayapat**[1]

[1]Department of Radiology, Faculty of Dentistry, Chulalongkorn University, Bangkok

## Abstract

***Objectives:*** To evaluate the accuracy of Tanner-Whitehouse method (TW3 RUS score) on Thai subjects.

***Methods:*** A total of 200 hand and wrist radiographs from patients who need orthodontic treatment or other treatments were collected at the Department of Radiology, Faculty of Dentistry, Chulalongkorn University. The subjects, defined as contemporary Thais, were 8-20 years old when the radiographs were taken. Age estimation was done using Tanner- Whitehouse 3, RUS score, method (TW3-RUS) by two calibrated observers. The observation was done twice with 4-week-time interval. Comparison between the chronological ages and the estimated ages by TW3-RUS method was done. Descriptive analysis was analyzed. Mean differences between the age estimated by TW3-RUS method and the chronological age were calculated. Wilcoxon signed ranks test and Spearman's correlation coefficient were used to compare the estimated age with the chronological age. Weighted kappa analysis was used to test the intra-observer and inter-observer reliability.

***Results:*** The mean difference between the estimated age and the chronological age showed an overall overestimation of 0.15 (standard deviation (SD) = 1.63) year. Wilcoxon signed ranks test showed statistically significant difference between the TW3-RUS estimated age and the chronological age ($p$ = 0.02). Spearman's correlation coefficient showed significant correlation between the TW3-RUS estimated age and the chronological age (rs = 0.86, $p < 0.001$). Good intra-observer reliability was found with weighted kappa of 0.813 - 0.941. Moderate to good inter-observer reliability was found with weighted kappa 0.674 - 0.946. Ulna bone showed the lowest inter-observer reliability (kappa value = 0.674).

***Conclusion:*** Significant differences were found between the estimated age using TW3-RUS method and the chronological age of a group of contemporary Thai children and adolescents. Further studies should be conducted on the adaptation of TW3-RUS method in order to improve its accuracy on Thai population.

**Keywords:** Age estimation, Hand and wrist radiography, Tanner-Whitehouse, Thai

**Received Date:** APR 27, 2017 **Accepted Date:** JUL 17, 2017

**doi:**

**Correspondence to:**

Pisha Pittayapat. Department of Radiology, Faculty of Dentistry, Chulalongkorn University 34 Henri-Dunant Road, Pathumwan, Bangkok 10330 Thailand Email address: p.pittayapat@gmail.com Tel: 081-814-2656

## Introduction

Age estimation is applied as an essential part in many situations, such as growth observation, human identification, immigrant registration and legal judgment. So far, pediatricians had collected data to find norms of skeletal development and introduced several age estimation methods to make a proper comparison with patients in order to evaluate their developmental status.[1-3] When an unknown body was found, information on estimated age would help screening for a person who is possibly the victim.[2,4]

In the medical aspect, skeletal and dental developments are referred as the representation of chronological age.[5] Morphological changes and developmental stages of bones are useful indicators as well as eruption and morphological development of teeth.[5] Age estimation by using hand and wrist radiography is considered as the first choice for many cases since it is uncomplicated, inexpensive and non-invasive.[5,6]

Human hand and wrist consists of 27 bones for each side of the body. The 19 bones of one hand can be counted into 5 metacarpuses, 5 proximal phalanges, 4 middle phalanges (absent in thumb finger), and 5 distal phalanges. The rest 8 bones, called carpal bones, belong to the wrist and are defined as capitate, hamate, pisiform, triquetrum, lunate, scaphoid, trapezium, and trapezoid. There is an exceptionally calcified mass found on the thumb called a sesamoid bone. Radius bone and ulnar bone are adjacent to the wrist and found on hand and wrist radiographs thus, are also used as developmental indicators.[7]

During long bone development, epiphyseal development are defined in stages: presenting, widening, capping (cover) at the end of diaphysis, and fusing with the diaphysis.[7] Unlike long bones, the morphological stages of carpal bones are not so empirical. The last change found in hand and wrist region is a complete fusion of distal epiphysis with diaphysis of radius bone at the age of 17 years in female and 19 years in male.[8] Therefore, hand and wrist cover almost 20 years of human development, from the time of newborn to the end of teenager.

Many age estimation methods using hand and wrist radiographs have been proposed.[8-10] Each method has its own pros and cons relying on which of the main concept it belongs. One of the most recently published methods and is well-known in the anthropological field is the "Tanner-Whitehouse method".[5,10-14]

Tanner-Whitehouse method refers to stages of skeletal growth focusing on regions on hand and wrist bones. Each stage of each region is represented by a number.[10,15] The numbers corresponding with the present bone stage from all regions are then summed together and compared with the sum score table correlated with the chronological age.[10,15] This method has been introduced in 3 editions called "TW1", "TW2" and "TW3". The latest edition (TW3) was published in 2001.[6,10] TW3 uses the new data which covers more varieties of ethnicity resulting in the new sum score table. TW3 is composed of 2 scoring systems which can be used separately: "radius, ulna, and selected metacarpal and phalanges (RUS) score", relying on 13 bone (Fig. 1) (Table 1) and "carpals (CAR) score", relying on 7 carpal bones.[6,10]

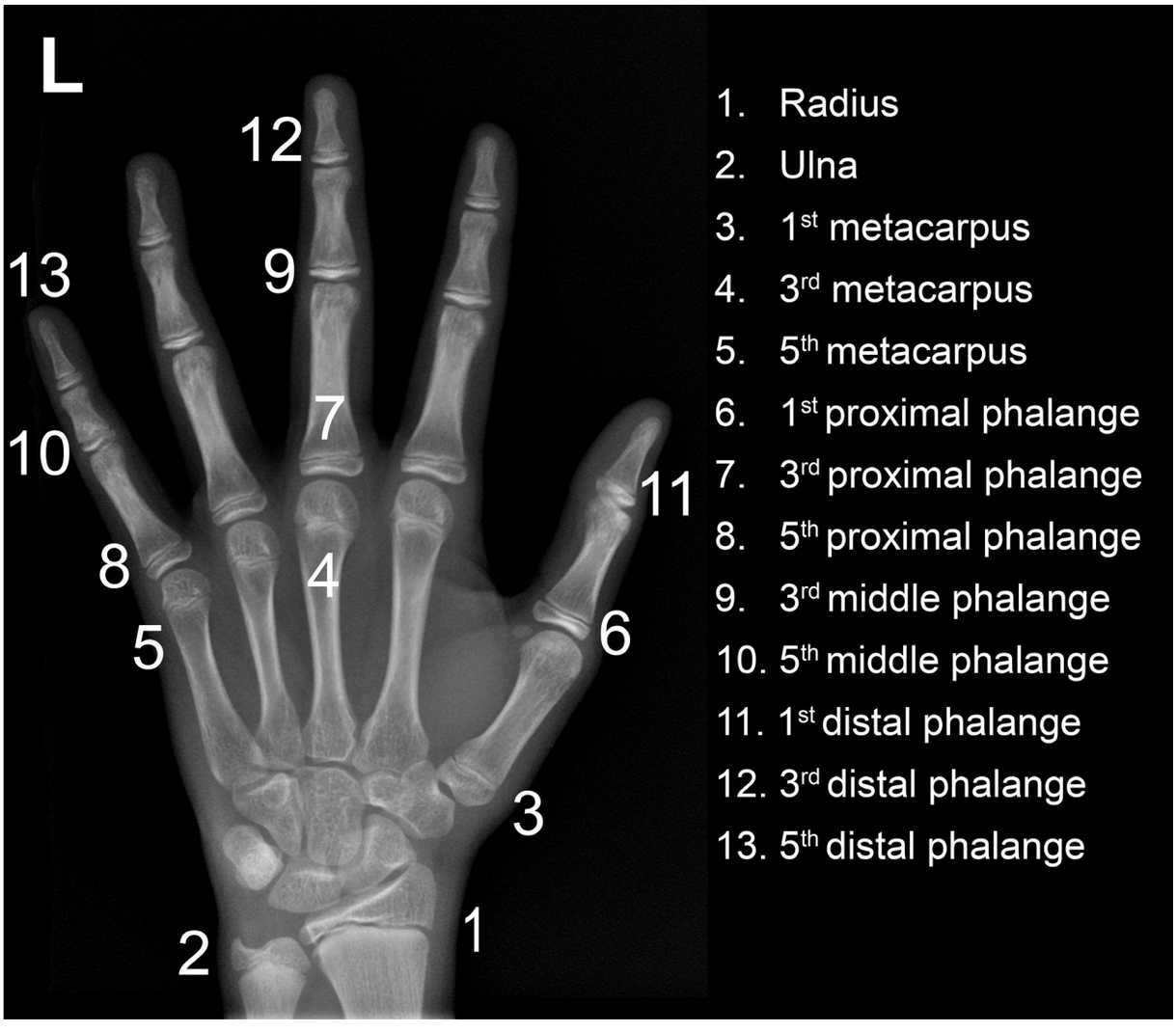


***Figure 1*** *An example of hand and wrist radiograph, showing 13 regions of interest of the hand and wrist bones according to Tanner and Whitehouse 3 (TW3-RUS) method. Each number referred to each bone: 1, Radius; 2, Ulna; 3, 1st metacarpus; 4, 3rd metacarpus; 5, 5th metacarpus; 6, 1st proximal phalange; 7, 3rd proximal phalange; 8, 5th proximal phalange; 9, 3rd middle phalange; 10, 5th middle phalange; 11, 1st distal phalange; 12, 3rd distal phalange; 13, 5th distal phalange. Stages based on TW3 definitions were given to each region and then translated to RUS scores (Table 1). Sums of the scores were then converted to age*

*Table 1* *RUS-score according to TW3-RUS method of male (M) and female (F) for each stage of each region on a hand and wrist radiograph*

| | | Stage | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | A | B | C | D | E | F | G | H | I |
| Radius | M | 0 | 16 | 21 | 30 | 39 | 59 | 87 | 138 | 213 |
| | F | 0 | 23 | 30 | 44 | 56 | 78 | 114 | 160 | 218 |
| Ulna | M | 0 | 27 | 30 | 32 | 40 | 58 | 107 | 181 | |
| | F | 0 | 30 | 33 | 37 | 45 | 74 | 118 | 173 | |
| 1st metacarpus | M | 0 | 6 | 9 | 14 | 21 | 26 | 36 | 49 | 67 |
| | F | 0 | 8 | 12 | 18 | 24 | 31 | 43 | 53 | 67 |
| 3rd metacarpus | M | 0 | 4 | 5 | 9 | 12 | 19 | 31 | 43 | 52 |
| | F | 0 | 5 | 8 | 12 | 16 | 23 | 37 | 47 | 53 |
| 5th metacarpus | M | 0 | 4 | 6 | 9 | 14 | 18 | 29 | 43 | 52 |
| | F | 0 | 6 | 9 | 12 | 17 | 23 | 35 | 48 | 52 |
| 1st proximal phalange | M | 0 | 7 | 8 | 11 | 17 | 26 | 38 | 52 | 67 |
| | F | 0 | 9 | 11 | 14 | 20 | 31 | 44 | 56 | 67 |
| 3rd proximal phalange | M | 0 | 4 | 4 | 9 | 15 | 23 | 31 | 40 | 53 |
| | F | 0 | 5 | 7 | 12 | 19 | 27 | 37 | 44 | 54 |
| 5th proximal phalange | M | 0 | 4 | 5 | 9 | 15 | 21 | 30 | 39 | 51 |
| | F | 0 | 6 | 7 | 12 | 18 | 26 | 35 | 42 | 51 |
| 3rd middle phalange | M | 0 | 4 | 6 | 9 | 15 | 22 | 32 | 43 | 52 |
| | F | 0 | 6 | 8 | 12 | 18 | 27 | 36 | 45 | 52 |
| 5th middle phalange | M | 0 | 6 | 7 | 9 | 15 | 23 | 32 | 42 | 49 |
| | F | 0 | 7 | 8 | 12 | 18 | 28 | 35 | 43 | 49 |
| 1st distal phalange | M | 0 | 5 | 6 | 11 | 17 | 26 | 38 | 46 | 66 |
| | F | 0 | 7 | 9 | 15 | 22 | 33 | 48 | 51 | 68 |
| 3rd distal phalange | M | 0 | 4 | 6 | 8 | 13 | 18 | 28 | 34 | 49 |
| | F | 0 | 7 | 8 | 11 | 15 | 22 | 33 | 37 | 49 |
| 5th distal phalange | M | 0 | 5 | 6 | 9 | 13 | 18 | 27 | 34 | 48 |
| | F | 0 | 7 | 8 | 11 | 15 | 22 | 32 | 36 | 47 |

Pinchi *et al.* compared skeletal age and chronological of Italian children and adolescents using Greulich and Pyle atlas method, TW2 and TW3.[16] The results showed the median differences for TW3 and GP methods were close to 0. No significant differences were found between estimated and chronological age for TW3. TW2 proved to be the worst among the three.[16]

Some factors may influence the accuracy of the predicted age. The factors that should be taken into account are genetic variations and generation differences.[5,6]

Genetic variations affect the progress on physiological development, including skeletal development, correlating with ages.[1,6] At least 2 aspects must be taken into account: sex and ethnicity. By sex,

many previous studies found that females usually grow faster than males.[1,2,14,17-22] By ethnicity, there are many studies finding differences in timing of growth spurt and rate of skeletal growth between ethnic groups.[2,5,6,11,19,23-25]

Generation differences also affect the accuracy of age estimation. Children developmental rate tended to be faster in younger generations.[1,2,26-28] Studies on recent generation showed age overestimation using the long time-practiced age estimation methods.[5,12,26,27] Hsieh *et al.* investigated the skeletal maturation of Taiwanese children from two generations using TW3 method.[27] It was found that the skeletal maturation of children in the mid-2000s is faster than that in the mid-1960s.[27]

Since Tanner-Whitehouse 3 (TW3) method was recently revised and is more applicable with multiple ethnic groups, but no study on Thai population has been published. Therefore, the aim of this study was to evaluate the accuracy of Tanner-Whitehouse method (TW3-RUS score) on a group of contemporary Thai children and adolescents.

## Materials and Methods

### *Samples*

Hand and wrist radiographs from patients who need orthodontic treatment or other treatments were collected at the Department of Radiology, Faculty of Dentistry, Chulalongkorn University. The radiographs were taken by Carestream™ CS 8000c and CS 9000c x-ray machine (Carestream Health, Inc, Rochester, NY, USA) using standard exposure parameters based on patients' size. The subjects were 8-20 years old when the radiographs were taken. Radiographs of left or right hand and wrist were both included since no significant difference was found when using them for age estimation.[8,29,30]

Selection criteria were set in order to control the influencing factors and the subjects were defined as "contemporary Thai". The patients must have declared Thai nationality and the hand and wrist radiographs must have been taken from 1st January 2011 to 31st December 2016. Therefore, the date of birth of all subjects must be between 1991 and 2008. Patients with history of systemic diseases that affect skeletal development were excluded.

### *Observations*

After the screening process, 200 hand and wrist radiographs were included in this study (98 males with mean age = 12.28 years, standard deviation (SD) = 2.26 years; 102 females, with mean age = 12.28 years, SD = 2.47 years) (Table 2). The included cases were randomized. Two pre-calibrated observers participated in the observation: one master student in dentomaxillofacial radiology and one dentomaxillofacial radiologist with 13 years experiences.

*Table 2* *Frequency of the subjects in each age group*

| Age (year) | Female | Male | Total |
|---|---|---|---|
| **8 – 8.99** | 7 | 7 | 14 |
| **9 – 9.99** | 9 | 9 | 18 |
| **10 – 10.99** | 18 | 10 | 28 |
| **11 – 11.99** | 15 | 22 | 37 |
| **12 – 12.99** | 17 | 13 | 30 |
| **13 – 13.99** | 16 | 21 | 37 |
| **14 – 14.99** | 6 | 5 | 11 |
| **15 – 15.99** | 5 | 5 | 10 |
| **16 – 16.99** | 3 | 3 | 6 |
| **17 – 17.99** | 3 | 1 | 4 |
| **18 – 18.99** | 1 | 1 | 2 |
| **19 – 19.99** | 1 | 1 | 2 |
| **20 – 20.99** | 1 | 0 | 1 |
| **Total** | 102 | 98 | 200 |

Age estimation was done using Tanner-Whitehouse 3, RUS score, method (TW3-RUS method) (Table 1) (Fig. 1).[10] The hand and wrist images were visualized using Infinitt® PACS software (Infinitt Healthcare Co., Ltd., Seoul, South Korea). During the estimation process the observers were blinded from the true (chronological) age leaving only the sex of the patients to be known. The first observer did the age estimation on the whole samples. Twenty-percent of the samples were then randomly selected for intra- and inter-observer analysis. The first observer did the second observation on the selected 20 % of the samples 4 weeks after the first observation. The second observer performed age estimation with this group of samples for inter-observer analysis.

***Statistical analysis***

Comparison between the chronological ages and the estimated ages by TW3-RUS method was done. Descriptive analysis was analyzed. The samples were categorized by the chronological age, 1-year-old-ranged for each group. In each group, the mean and standard deviation of the estimated age and the chronological age were calculated. Mean differences between the age estimated by TW3-RUS method and the chronological age were also calculated. To evaluate the accuracy of the TW3-RUS age estimation method, Wilcoxon signed ranks test was used to compare the estimated age with the chronological age. The significance was set at $p<0.05$. The correlation between the estimated age and the chronological age was analyzed by Spearman's rank-order correlation. Weighted kappa analysis was used to test the intra-observer and inter-observer reliability.

## Results

***Tanner-Whitehouse 3, RUS score age estimation technique***

The mean chronological age, mean TW3-RUS estimated age and mean age difference for each age group were shown (Table 3 - 5).

***Table 3*** *Mean and standard deviation (SD) of chronological age, TW3-RUS estimated age and mean differences (TW3-RUS estimated age – chronological age) for each age group regardless of sex*

| Age group (year) | Mean chronological age ± SD (year) | Mean TW3-RUS estimated age ± SD (year) | Mean difference ± SD (year) |
|---|---|---|---|
| **8 – 8.99** | 8.63 ± 0.29 | 8.14 ± 1.79 | -0.49 ± 1.76 |
| **9 – 9.99** | 9.58 ± 0.22 | 9.62 ± 1.88 | 0.04 ± 1.86 |
| **10 – 10.99** | 10.42 ± 0.29 | 10.35 ± 1.53 | -0.08 ± 1.57 |
| **11 – 11.99** | 11.45 ± 0.33 | 11.81 ± 1.44 | 0.36 ± 1.42 |
| **12 – 12.99** | 12.40 ± 0.30 | 13.15 ± 1.35 | 0.75 ± 1.29 |
| **13 – 13.99** | 13.46 ± 0.26 | 14.45 ± 0.38 | 0.73 ± 1.54 |
| **14 – 14.99** | 14.45 ± 0.38 | 14.96 ± 1.12 | 0.52 ± 0.97 |
| **15 – 15.99** | 15.54 ± 0.36 | 15.42 ± 0.98 | -0.12 ± 0.97 |
| **16 – 16.99** | 16.26 ± 0.32 | 15.75 ± 0.82 | -0.51 ± 0.66 |
| **17 – 17.99** | 17.39 ± 0.18 | 15.38 ± 0.75 | -2.01 ± 0.63 |
| **18 – 18.99** | 18.58 ± 0.38 | 15.75 ± 1.06 | -2.83 ± 0.69 |
| **19 – 19.99** | 19.64 ± 0.21 | 15.75 ± 1.06 | -3.89 ± 0.86 |
| **20 – 20.99** | 20.15* | 15.00* | -5.15* |
| **overall** | 12.28 ± 2.37 | 12.43 ± 2.64 | 0.15 ± 1.63 |

**only one subject present in the study*

***Table 4*** *Mean and standard deviation (SD) of chronological age, TW3-RUS estimated age and mean differences (TW3-RUS estimated age – chronological age) for male subjects*

| Age group (year) | Mean chronological age ± SD (year) | Mean TW3-RUS estimated age ± SD (year) | Mean difference ± SD (year) |
|---|---|---|---|
| **8 – 8.99** | 8.63 ± 0.34 | 8.34 ± 1.88 | -0.28 ± 1.75 |
| **9 – 9.99** | 9.56 ± 0.23 | 9.07 ± 2.25 | -0.49 ± 2.27 |
| **10 – 10.99** | 10.51 ± 0.32 | 9.27 ± 1.24 | -1.24 ± 1.27 |
| **11 – 11.99** | 11.51 ± 0.33 | 11.35 ± 1.64 | -0.16 ± 1.54 |
| **12 – 12.99** | 12.37 ± 0.32 | 13.09 ± 1.81 | 0.71 ± 1.74 |
| **13 – 13.99** | 13.47 ± 0.27 | 13.94 ± 2.01 | 0.47 ± 1.92 |
| **14 – 14.99** | 14.54 ± 0.39 | 15.52 ± 1.08 | 0.98 ± 0.95 |
| **15 – 15.99** | 15.42 ± 0.41 | 15.84 ± 1.31 | 0.42 ± 1.14 |
| **16 – 16.99** | 16.45 ± 0.39 | 16.50 ± 0.00 | 0.05 ± 0.39 |
| **17 – 17.99** | 17.60* | 16.50* | -1.10* |
| **18 – 18.99** | 18.80* | 16.50* | -2.30* |
| **19 – 19.99** | 19.80* | 16.50* | -3.30* |
| **All males** | 12.28 ± 2.26 | 12.26 ± 2.98 | -0.03 ± 1.75 |

**only one subject present in the study*

***Table 5*** *Mean and standard deviation (SD) of chronological age, TW3-RUS estimated age and mean differences (TW3-RUS estimated age – chronological age) for female subjects*

| Age group (year) | Mean chronological age ± SD (year) | Mean TW3-RUS estimated age ± SD (year) | Mean difference ± SD (year) |
|---|---|---|---|
| **8 – 8.99** | 8.63 ± 0.26 | 7.93 ± 1.81 | -0.71 ± 1.87 |
| **9 – 9.99** | 9.59 ± 0.24 | 10.18 ± 1.32 | 0.58 ± 1.24 |
| **10 – 10.99** | 10.37 ± 0.27 | 10.94 ± 1.35 | 0.57 ± 1.35 |
| **11 – 11.99** | 11.35 ± 0.31 | 12.49 ± 0.68 | 1.14 ± 0.72 |
| **12 – 12.99** | 12.42 ± 0.28 | 13.20 ± 0.91 | 0.78 ± 0.87 |
| **13 – 13.99** | 13.44 ± 0.27 | 14.52 ± 0.71 | 1.08 ± 0.74 |
| **14 – 14.99** | 14.37 ± 0.40 | 14.50 ± 1.00 | 0.13 ± 0.89 |
| **15 – 15.99** | 15.65 ± 0.30 | 15.00 ± 0.00 | -0.65 ± 0.30 |
| **16 – 16.99** | 16.07 ± 0.02 | 15.00 ± 0.00 | -1.07 ± 0.02 |
| **17 – 17.99** | 17.32 ± 0.15 | 15.00 ± 0.00 | -2.32 ± 0.15 |
| **18 – 18.99** | 18.30* | 15.00* | -3.30* |
| **19 – 19.99** | 19.50* | 15.00* | -4.50* |
| **20 – 20.99** | 20.15* | 15.00* | -5.15* |
| **All females** | 12.28 ± 2.47 | 12.60 ± 2.27 | 0.32 ± 1.50 |

**only one subject present in the study*

Comparison between the TW3-RUS estimated age and the chronological age showed overall overestimation of 0.15 year. The mean difference for female subjects was 0.32 (SD = 1.50) year and -0.03 (SD = 1.75) year for male subjects. The data was not normally distributed (from Shapiro-Wilk test), thus Wilcoxon signed ranks test was selected to analyze the difference. The results showed statistically significant difference between the TW3-RUS estimated age and the chronological age ($p$ = 0.02).

Based on the different age groups (Table 3), the differences between the chronological age and the estimated age can be categorized in 3 parts. The first part was 8 - 10 years group which the TW3-RUS age showed an underestimating trend. The estimated age of this part was -0.14 (SD = 1.69) year. The second part was between 11 and 15 years that overestimation was found in the majority. The mean difference in this part was 0.60 (SD = 1.39) year. The final part, 15 -20 years old expressed an overall underestimation of 1.23 (SD = 1.65) year.

### *Correlations between the chronological age and the estimated age*

The results from Spearman's correlation coefficient analysis showed significant correlation between the TW3-RUS estimated age and the chronological age for both male and female subjects ($p$ < 0.001) (Table 6). The overall correlation coefficient (rs) was 0.86.

***Table 6*** *Correlation coefficient (rs) and p-value from Spearman's rank-order coefficient analysis*

| sex | Correlation coefficient (rs) | *p*-value |
|---|---|---|
| **All** | 0.86 | < 0.001 |
| **Male** | 0.85 | < 0.001 |
| **Female** | 0.91 | < 0.001 |

### *Intra- and inter-observer reliability*

Weighted kappa analysis showed good agreement for the intra-observer reliability and moderate to good agreement for inter-observer reliability. The agreements on staging were separately analyzed for each bone (Table 7). The result for intra-observer analysis ranged from 0.813 to 0.941 that the third distal phalange showed the lowest reliability and the fifth proximal phalange had the highest reliability. The inter-observer reliability results showed kappa values 0.674 - 0.946. The ulna showed the lowest inter-observer reliability and the first metacarpus showed the highest reliability.

***Table 7*** *Weighted kappa results for intra-observer and inter-observer reliability*

| | Intra-observer reliability | Inter-observer reliability |
|---|---|---|
| **Radius** | 0.858 | 0.783 |
| **Ulna** | 0.848 | 0.674 |
| **1st metacarpus** | 0.854 | 0.946 |
| **3rd metacarpus** | 0.852 | 0.707 |
| **5th metacarpus** | 0.879 | 0.807 |
| **1st proximal phalange** | 0.894 | 0.909 |
| **3rd proximal phalange** | 0.926 | 0.863 |
| **5th proximal phalange** | 0.941 | 0.896 |
| **3rd middle phalange** | 0.925 | 0.849 |
| **5th middle phalange** | 0.933 | 0.876 |
| **1st distal phalange** | 0.909 | 0.881 |
| **3rd distal phalange** | 0.813 | 0.833 |
| **5th distal phalange** | 0.893 | 0.829 |

## Discussion

In the present study, total of 200 hand and wrist radiographs from a group of contemporary Thai children and adolescents were investigated. Age estimation by TW3-RUS method was accomplished for all samples and then compared with the chronological age.

The TW3-RUS score was claimed to be more reliable than CAR score.[10] The development of short bones are more consistent than the carpal bones and only 11 short bones with radius and ulna are enough for age estimation.[10] In addition, the morphological differentiation of carpal bones reaches their limits earlier than of the radius and ulna, making narrower range of age prediction in CAR score. From these reasons, TW3-RUS score was chosen in this study.

The results showed a statistically significant difference between the TW3-RUS estimated age and the chronological age ($p$ = 0.02) with average mean age difference of -0.03 (SD = 1.75) year for males and 0.32 (SD = 1.50) year for females. This was possibly due to the effect of ethnicity on skeletal maturation. Nutritional factors and socio-economic condition of people in different countries might also play a role. TW3-RUS method was studied based on European and American population whose ethnicity was Caucasian.[10] The ethnicity of Thais is mostly Southeast Asian. A few studies on Mongoloid populations were done using TW3 methods.[31] Kim *et al.* published a study on Korean children. The researchers compared the reliability of the Greulich and Pyle method, TW3 method and Korean standard bone age chart.[32] Significant correlations were found between chronological age and bone age estimated by all three methods. However, the study used samples whose age ranged between 7-12 years old and were all Mongoloid from Korean. Differences of the characteristics of the samples could explain the reason why the results were not corresponding to the result of the present study.[32] An Asian study in China found a significant different between the chronological age and TW3 estimated age.[33] Zhang *et al.* evaluated bone age of Han Chinese children aged 1-20 years. It was found that the skeletal maturity of the Chinese boys and girls differed significantly from that of TW3 after 6 years for boys and 10 years for girls.[33] Their results were corresponding to ours although the present study could not include children whose age younger than 8 years old. Han Chinese is one of the Chinese ethnicities that distributed in the Southeast Asian countries thus might explain the similar trend of results.

However, a few studies showed no significant differences.[16,34] Pinchi *et al.* found no significant differences between the estimated age and chronological age for TW3.[16] Haiter-Neto *et al*. evaluated three age estimation methods: Greulich and Pyle, TW3 and Eklöf and Ringertz.[34] Results showed no significant difference between the chronological age and the estimated age using the three methods.[34] The main factor that led the results to another direction might be from the differences in ethnicities of the samples (Italian, Brazilian) and their socio-economic condition and nutritional factors.

Another factor which may contribute to the discrepancy in the results is the generation difference. The present study refers 'contemporary' as the people born between 1991 and 2008. TW3 method was proposed in 2001.[10] The reference samples in the method must have born in 1960s – 1990s. The effect of secular change cannot be left out as there is a huge difference in nutritional shift just within one decade. A study on the effect of secular change on skeletal maturation was done by Hsieh *et al.* on Taiwanese children using TW3 method.[27] The authors concluded that the skeletal maturation of children in the mid-2000s was faster than that in the mid-1960s. The authors also suggested that the causes of the differences might be the difference in socio-economic status and difference in food consumption between the two generations.[27]

The present research is a retrospective study. The hand and wrist radiographs in this study were primarily taken for an evaluation of skeletal growth prior to orthodontic treatment. On some radiographs the position of the hands was not strictly adjusted; therefore, some bones were not aligned totally parallel to the image receptor, making it difficult to visualize the stages of bone development (e.g. capping, partial fusion of epiphysis and diaphysis) due to the overlapping and superimposition of bones. The thumb finger was the most problematic part as the finger torsion was different from which was illustrated in the original TW3 method.[10] However, the overall quality of the radiographs was acceptable.

Observer dependence is another factor that might influence the reliability of the estimated age.[6,35-38] In this study, kappa analysis showed good intra-observer reliability and moderate to good inter-observer reliability (Table 7). The ulna bone showed lowest reliability for both intra- and inter-observer agreement. Experiences of the observers on hand and wrist radiography also played a role despite a calibration session performed prior to the observation. The definition of radiographic findings between different stages might be unclear and can still be improved.

The Spearman's analysis proved the presence of correlation between the estimated age and the chronological age, showing that TW3-RUS method was still applicable for contemporary Thais. However, since Wilcoxon signed ranks test showed that the result from the TW3-RUS age estimation was significantly different from the chronological age, some adaptation should be applied to the estimation process in case of Thai subjects. Firstly, a suggestion was made to adapt TW3-RUS for Thai population by adding the mean difference to the original result based on the age group which may increase or decrease the final predicted age. However, care must be taken when adding the mean difference to the predicted age. A validation of this adaptation still needs to be proven with more scientific evidence on another group of Thai population.

Secondly, this study showed that the skeletal age tended to be underestimated in subjects over 17 years because the maximum predicted ages of the TW3 method are 15 years old in girls and 16.5 years old in boys. Therefore, if every bone reaches the highest stage, especially if radius and ulna showed complete fusion, the result is rather unreliable and may only be concluded that the predicted age is a minimal estimated age for the individual.

Although the estimated age in this study was statistically significant different from the chronological age, TW3-RUS method showed a potential to be used on Thai children and adolescents. Further studies should still be done in order to adapt and possibly simplify TW3 method to be more applicable for Thais. In addition, the carpal bones in TW3-CAR method as claimed to be more consistent between ethnicities should also be further studied and to compare with results from TW3-RUS scoring method.

## Conclusion

Significant differences were found between the estimated age using TW3-RUS method and the chronological age of a group of contemporary Thai children and adolescents. Further studies should be conducted on the adaptation of TW3 method in order to improve its accuracy on Thai population.


## Acknowledgement

The Scholarship from the Graduate School, Chulalongkorn University to commemorate the 72nd anniversary of his Majesty King Bhumibala Aduladeja is gratefully acknowledged.

## References


1. Berk LE. Child development. 9 ed. London, UK: Pearson Education; 2012.

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

3. Kliegman RM, Stanton BF, St Geme JW, Schor NF. Nelson textbook of pediatrics. 20 ed. Philadelphia, PA: Elsevier; 2015.

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

5. 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.

6. Hackman L. Age estimation in the living: a test of 6 radiographic methods: University of Dundee; 2012.

7. Schoenwolf GC, Bleyl SB, Brauer PR, Francis-West PH. Larsen's human embryology. Philadelphia, PA: Elsevier Health Sciences; 2014.

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

9. Fishman LS. Maturational patterns and prediction during adolescence. ***Angle Orthod*** 1987;57:178-93.

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

11. Buken B, Safak AA, Buken E, Yazici B, Erkol Z, Erzengin ÖU. Is the Tanner–Whitehouse (TW3) method sufficiently reliable for forensic age determination of Turkish children? ***Turk J Med Sci*** 2010;40:797-805.

12. 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.

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

14. Molinari L, Gasser T, Largo RH. TW3 bone age: RUS/CB and gender differences of percentiles for score and score increments. ***Ann Hum Biol*** 2004;31:421-35.

15. Tanner JM, Whitehouse R, Marshall W, Healty M, Goldstein H. Assessment of skeletal maturity and prediction of adult height (TW2 method). Cambridge, MA: Academic Press; 1975.

16. Pinchi V, De Luca F, Ricciardi F, Focardi M, Piredda V, Mazzeo E, *et al.* Skeletal age estimation for forensic purposes: A comparison of GP, TW2 and TW3 methods on an Italian sample. ***Forensic Sci Int*** 2014;238:83-90.

17. Beunen GP, Rogol AD, Malina RM. Indicators of biological maturation and secular changes in biological maturation. ***Food Nutr Bull*** 2006;27:S244-56.

18. Bogin B, MacVean RB. The relationship of socioeconomic status and sex to body size, skeletal maturation, and cognitive status of Guatemala City school children. ***Child Dev*** 1983;54:115-28.

19. Cole TJ, Rousham EK, Hawley NL, Cameron N, Norris SA, Pettifor JM. Ethnic and sex differences in skeletal maturation among the Birth to Twenty cohort in South Africa. ***Arch Dis Child*** 2015;100:138-43.

20. Fitzpatrick LA. Sex differences in skeletal development. Advances in Molecular and Cell Biology. Volume 34. Amsterdam, Netherland: Elsevier; 2004. p. 229-45.

21. Flory CD. Sex differences in skeletal development. ***Child Dev*** 1935;6:205-12.

22. Flory CD. Osseous Development in the Hand as an Index of Skeletal Development. ***Monogr Soc Res Child Dev*** 1936;1:i+iii-ix+1-141.

23. 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.

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

25. 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.
26. 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.
27. 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.
28. Lai EHH, Chang JZC, Yao CCJ, Tsai SJ, Liu JP, Chen YJ, *et al.* Relationship between age at menarche and skeletal maturation stages in Taiwanese female orthodontic patients. ***J Formos Med Assoc*** 2008;107:527-32.
29. 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.
30. 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.
31. Serinelli S, Panetta V, Pasqualetti P, Marchetti D. Accuracy of three age determination X-ray methods on the left hand-wrist: a systematic review and meta-analysis. ***Leg Med (Tokyo)*** 2011;13:120-33.
32. Kim JR, Lee YS, Yu J. Assessment of bone age in prepubertal healthy Korean children: comparison among the Korean standard bone age chart, Greulich-Pyle method, and Tanner-Whitehouse method. ***Korean J Radiol*** 2015;16:201-5.
33. Zhang SY, Liu LJ, Wu ZL, Liu G, Ma ZG, Shen XZ, *et al.* Standards of TW3 skeletal maturity for Chinese children. ***Ann Hum Biol*** 2008;35:349-54.
34. Haiter-Neto F, Kurita LM, Menezes AV, Casanova MS. Skeletal age assessment: a comparison of 3 methods. ***Am J Orthod Dentofacial Orthop*** 2006;130:435 e15-20.
35. Alcina M, Lucea A, Salicrú M, Turbón D. Reliability of the Greulich & Pyle method for bone age estimation in a Spanish sample. ***J Forensic Leg Investig Sci*** 2015;1:1-6.
36. King DG, Steventon DM, O'Sullivan MP, Cook AM, Hornsby VP, Jefferson IG, *et al.* Reproducibility of bone ages when performed by radiology registrars: an audit of Tanner and Whitehouse II versus Greulich and Pyle methods. ***Br J Radiol*** 1994;67:848-51.
37. Kim SY, Oh YJ, Shin JY, Rhie YJ, Lee KH. Comparison of the Greulich-Pyle and Tanner Whitehouse (TW3) methods in bone age assessment. ***J Korean Soc Pediatr Endocrinol*** 2008;13:50-5.
38. Paxton ML, Lamont AC, Stillwell AP. The reliability of the Greulich–Pyle method in bone age determination among Australian children. ***J Med Imaging Radiat Oncol*** 2013;57:21-4.