Age estimation at 18-year threshold: comparing Demirjian and Cameriere's methods for Thais

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The authors declare that they have no conflict of interest.

KEYWORDS

Forensic odontology, Dental age estimation, Demirjian's method, Cameriere's method, Mandibular third molars

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ABSTRACT

This study aims to compare the accuracy of Demirjian's and Cameriere's methods in determining adult age at the 18-year threshold using mandibular third molars in the Thai population. Panoramic radiograph images of 504 healthy subjects aged between 14 and 23 years were retrospectively collected. The developmental stages of mandibular third molars were evaluated using Demirjian's method, while the maturity index of mandibular third molars (I_{3M}) was assessed using Cameriere's method. Comparing the development of the left and right mandibular third molars, slight differences were observed: the left side developed 0.06 stages faster ($p = 0.01$) and had an I_{3M} 0.01 higher ($p < 0.01$). For the 18-year age threshold, Demirjian's Stage H demonstrated a specificity of 1.00 for both sexes on the left mandibular third molar, and 0.97 for males and 1.00 for females on the right. $I_{3M} < 0.08$ yielded specificities of 0.84 for males and 0.93 for females on the left, and 0.82 for males and 0.91 for females on the right. Reducing the cut-off to $I_{3M} < 0.02$ improved specificity to 1.00 for both sexes on the left side, and 0.96 for males and 1.00 for females on the right. Notably, using Demirjian's Stage H and $I_{3M} < 0.02$, the probability of being over 18 years was 1.00 for females on both sides, and 0.96 for males on the left and 1.00 on the right. Our study recommends using an I_{3M} cutoff of <0.02 for adult age assessment in the Thai population, as it achieves high specificity comparable to Demirjian's Stage H, with effective differentiation of adults.

INTRODUCTION

Accurate forensic age estimation for living individuals holds significant importance, both for the individuals undergoing examination and for society as a whole. It plays a crucial role in various contexts, including civil procedures, criminal investigations, and asylum cases.[1] Established protocols for age estimation in living adolescents and young adults are instrumental in ensuring justice, protecting individuals' rights, and facilitating informed decision-making in legal procedures.[2] In legal contexts involving young individuals, the age of 18 is widely recognised as a critical legal threshold. Internationally, the United Nations Convention on the Rights of the Child designates 18 as the age to categorise individuals as children or adults in legal contexts. In Thailand, this age holds significance in accordance with the Juvenile and Family Court and Its

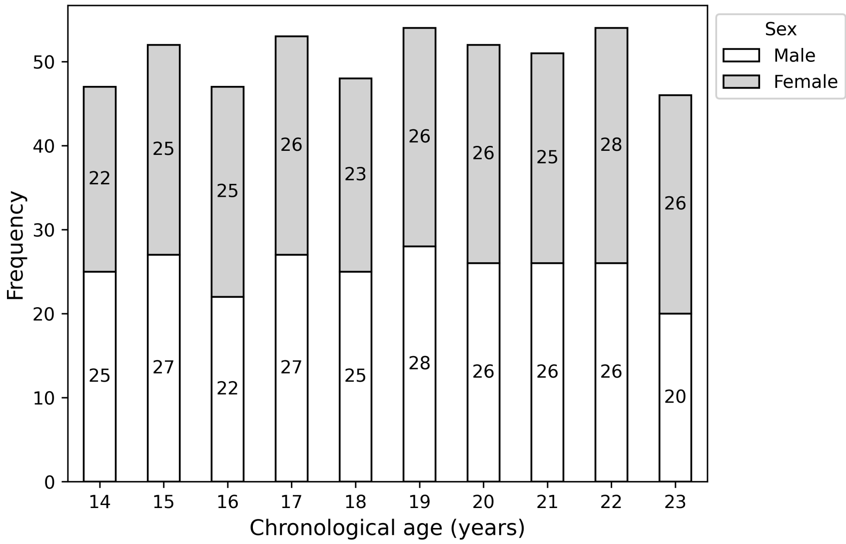
Procedure Act, B.E. 2553. Therefore, this threshold impacts the legal procedure, potential sentencing and fundamental rights.
Dental age estimation is particularly useful because tooth development is influenced more by genetics than environmental factors and hormones, making teeth a reliable indicator of age.[3] Dental age estimation methods, such as assessing dental developmental stages[4] or measuring the open apices of developing teeth,[5] can be applied in young individuals. However, beyond the age of 17, most teeth undergo complete development, except for the third molars.[6] Hence, third molars are considered a key predictor for age estimation in teenagers and young adults. Current dental age estimation studies in the Thai population primarily rely on assessing tooth development stages of third molars.[7-10] Notably, Duangto et al. (2016)[7] utilised Demirjian's classification to estimate dental age from mandibular third molars, reporting that individuals with Stage H mandibular third molars were all confirmed to be over 18 years old. However, this method might suffer from limitations in sensitivity. Cameriere et al. (2008)[11] proposed the Third Molar Maturity Index (I_{3M}) as an alternative and compared this method against Demirjian's developmental stage-based method. I_{3M} achieved comparable specificity with Demirjian's method while exhibiting higher sensitivity, potentially minimising misclassifications. The proposed cut-off value of I_{3M} less than 0.08 allows for precise identification of individuals at the critical 18-year threshold.
Accurate dental age estimation relies on population-specific data, as methods effective in one group may not translate well to others due to genetic and environmental variations.[12] While the I_{3M} demonstrates promising potential exceeding Demirjian's method, its effectiveness remains untested in the Thai population. This critical lack of population-specific data hinders the confident application of I_{3M} for age estimation in Thai legal contexts. Therefore, this study aims to compare the applicability of Demirjian's and Cameriere's methods for identifying adults at the critical 18-year threshold within the Thai population. Identifying the most accurate approach can offer a valuable tool for legal proceedings, minimising the risk of misclassifying individuals and contributing to fairer and more accurate legal outcomes.

MATERIALS AND METHODS

Ethical approval and study sample

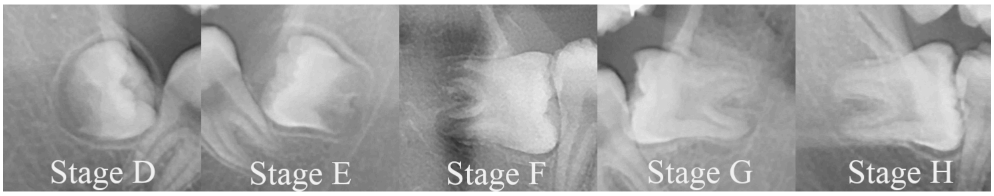
The research protocol received approval from the Human Research Ethics Committee (protocol EC6604-024) at the Faculty of Dentistry, Prince of Songkla University. This study retrospectively collected panoramic radiographs from the Radiology Clinic at the Faculty of Dentistry, Prince of Songkla University from 2018 to 2024. Two radiographic units were used to capture the radiographic images: GXDP-700 (Gendex Dental Systems, Hatfield, Pennsylvania, USA), and Orthopantomograph OP300 (Instrumentarium Dental, Charlotte, North Carolina, USA). These radiographs were exported from the system in JPEG file format. In addition, data including sex, date of birth, and radiographic were collected. Chronological age was calculated by subtracting the date of birth from the radiographic date. All collected data underwent anonymisation and were kept confidential.
Sample size determination was conducted using R Project for Statistical Computing,[13] with epiR package.[14] The calculation was based on the specificity of I_{3M} in age group assessment derived from Scendoni et al.'s study,[15] with an estimated prevalence of 0.6, an epsilon value of 0.05, and a confidence level of 95%. The minimum required sample size was 490. Therefore, this study employed stratified random sampling to recruit participants. The radiographic prescription lists from the Radiology clinic served as the sampling frame. We stratified the sample by both age and sex. For age, the sample was divided into groups ranging from 14 to 23 years. Individuals were then randomly selected from each stratum defined by age and sex to ensure a representative sample across the targeted demographic. The exclusion criteria encompassed poor radiographic quality, absence of both left and right mandibular third molars, severe buccoversion or linguoversion, the presence of dental or bone pathology in the area of interest, and the existence of developmental or systemic diseases that could potentially impact tooth development. A total of 504 Thai healthy samples (252 males and 252 females) were included in this study (Fig. 1).

Figure 1. Distribution of the sample by age and sex



Radiographic assessment
Radiographic assessment involved two methods: Demirjian's and Cameriere's. For Demirjian's method, mandibular third molars were evaluated based on developmental stages (Stages A to H). In this study, the collected samples only exhibited Stages D to H, corresponding to the age of the samples (Fig. 2).

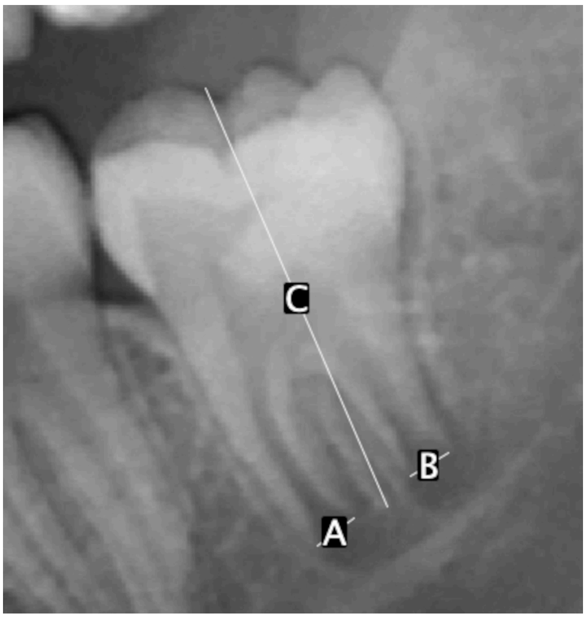
Figure 2. Examples of mandibular third molars Stages D to H according to Demirjian's classification



In Cameriere's method, determination of I_{3M} occurred in two instances. For complete root formation with a closed root apex, I_{3M} was designated as 0. In cases of incomplete root formation, I_{3M} was calculated by summing the distance from the inner to the inner surface of the root apex opening of each root (A+B) and dividing it by the tooth length (C) (Fig. 3). Measurements were conducted using ImageJ software.[16]

Two observers (KK and KC) evaluated tooth development using Demirjian's method, while measurement following Cameriere's method was performed by two different observers (AC and TP). All observers underwent calibration with an oral radiologist (WU), possessing five years of clinical experience, serving as the referee, before the commencement of the investigation. To assess inter-observer reliability, 50 radiographs were randomly selected. A month after the completion of the investigation, observers conducted a re-evaluation of the radiographs to determine intra-observer reliability.

Figure 3. An example of third molar maturity index measurements: A and B depict the distance of the open apices, while C illustrates tooth height



Statistical analysis

Cohen's kappa coefficient and intra-class correlation coefficient (ICC) were employed to assess the intra- and inter-observer reliability of Demirjian's and Cameriere's methods, respectively. The level of agreement was interpreted following Landis and Koch's guideline[17] for Cohen's kappa coefficient and Koo and Li's guideline[18] for ICC, respectively. Normality of the data was assessed using the Kolmogorov-Smirnov test for samples larger than 50 and the Shapiro-Wilk test for samples of 50 or fewer. Parametric statistics were employed for normally distributed data, while non-parametric statistics were used for data that did not follow a normal distribution.

Since the distributions of chronological age and I_{3M} for both the left and right mandibular third molars were non-normal ($p < 0.001$), and Demirjian's developmental stages are ordinal, Spearman's rank correlation was used to assess correlations between Demirjian's stages and chronological age, as well as between I_{3M} and chronological age. The independent t-test was applied for comparing age differences between males and females in groups with normal distribution, while the Mann-Whitney U test was used for non-normal distributions. For patients with both mandibular third molars, the Wilcoxon signed-rank test compared development between sides for both Demirjian's stages and I_{3M}, due to the non-normal distribution of I3M data on both sides ($p < 0.001$).

The performance of Demirjian's developmental stage and I_{3M} in predicting age groups at the 18-year threshold was evaluated using sensitivity, specificity, accuracy, positive predictive value, and negative predictive value. Furthermore, Bayes post-test probability (p) was employed to determine the likelihood of individuals reaching the age of 18 years according to the two methods. This probability can be calculated as follows:

$$p = \frac{Se \times p_0}{Se \times p_{0} + (1-Sp)(1-p_0)}$$

Where Se represents sensitivity and Sp represents specificity. Here, *po* represents the probability of individuals being over 18 years old within the age range of 14 to 23 years. According to the Thai National Statistical Office, the values of po for males and females are reported as 0.60 and 0.61, respectively. (http://statbbi.nso.go.th/).

The statistical analysis and data visualisation was performed within Jupyter Notebook, employing the NumPy, Pandas, SciPy, MatPlotLib, and Seaborn libraries.

RESULTS

The inter-observer reliability of Demirjian's method was almost perfect, with a kappa value of 0.92. The kappa values for intra-observer reliability of the method were 0.93 (KC) and 0.92 (KK), indicating almost perfect agreement. For Cameriere's method, the inter-observer reliability yielded an ICC value of 0.99, interpreted as excellent agreement. The ICC values for intra-observer reliability were 0.99 (TP) and 1.00 (AC), indicating excellent agreement.

Table 1 and Fig. 4 illustrate the distribution of chronological age within each of Demirjian's developmental stages for the left and right mandibular third molars. The Spearman correlation coefficient between developmental stage and chronological age for the left mandibular third molar was 0.79 ($p < 0.01$) for males and 0.71 ($p < 0.01$) for females. These correlations for the right mandibular third molar were 0.82 ($p < 0.01$) for males and 0.78 ($p < 0.01$) for females, respectively. In the left mandibular third molar, there were no statistically significant differences in chronological age between males and females within each stage, except for Stage F ($p < 0.001$), where the median age of females was 1.67 years older than that of males. On the right side, differences in chronological age between sexes were observed at Stage G ($p = 0.017$), with females being 0.72 years older than males.

Table 1. Summary of descriptive statistics for chronological age (in years) and a comparison between males and females in each of Demirjian's developmental stages for the left and right mandibular third molars (tooth 38 and 48)

Demirjian's stage	Male				Female				p-value[b]
	N	Mean ± SD (years)	Median (years)	p-value[a]	N	Mean ± SD (years)	Median (years)	p-value[a]	
Tooth 38									
D	7	14.67 ± 0.50	14.49	0.201	16	15.12 ± 0.99	14.82	0.020†	0.300
E	20	15.35 ± 0.82	15.35	0.735	37	16.17 ± 1.74	15.94	0.007†	0.078
F	81	17.17 ± 1.82	16.85	<0.001†	76	18.49 ± 2.34	18.52	<0.001†	<0.001*
G	70	20.09 ± 1.90	19.80	<0.001†	61	20.49 ± 2.24	21.13	<0.001†	0.183
H	54	21.53 ± 1.43	21.72	<0.001†	35	21.71 ± 1.30	21.77	0.510	0.597
Tooth 48									
D	10	14.80 ± 0.66	14.66	0.145	13	15.23 ± 1.24	14.84	0.014†	0.420
E	21	15.38 ± 0.83	15.14	0.117	34	15.86 ± 1.39	15.73	0.048†	0.291
F	66	16.95 ± 1.68	16.80	<0.001†	65	17.73 ± 2.09	17.60	<0.001†	0.039
G	67	19.53 ± 1.90	19.55	<0.001†	63	20.36 ± 2.03	20.27	<0.001†	0.017*
H	62	21.63 ± 1.51	22.01	<0.001†	39	22.03 ± 1.48	22.14	0.020†	0.186

N number of samples, *SD* standard deviation
[a] p-value for normality test: Shapiro-Wilk test for N < 50; Kolmogorov-Smirnov test for N ≥ 50.
[b] p-value for comparing mean age between males and females: use an independent t-test if normality is met; otherwise, use the Mann-Whitney U test.
† p-value <0.05 indicates a significant deviation from normality, suggesting that the data is not normally distributed.
* p-value <0.05 indicates a statistically significant difference.

Figure 4. Boxplot illustrating the relationship between chronological age and Demirjian's developmental stage of the left and right mandibular third molars, stratified by sex

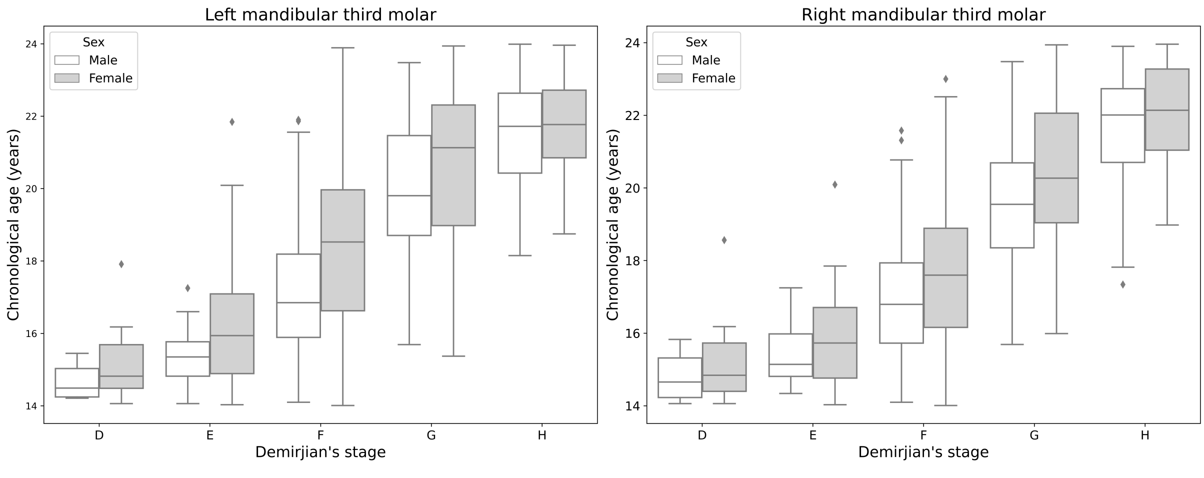


Table 2 and Fig. 5 illustrate the distribution of chronological age within each group of I_{3M}. The Spearman correlation coefficients between I_{3M} and chronological age were -0.81 ($p < 0.01$) for males and -0.79 ($p < 0.01$) for females on the left side. Correspondingly, for the right mandibular third molar, these coefficients were -0.83 ($p < 0.01$) for males and -0.82 ($p < 0.01$) for females. In the analysis of age differences between males and females for the left mandibular third molar, statistically significant differences were found in the I3M groups [0.08, 0.3) (p = 0.047), [0.04, 0.08) (p = 0.011), and [0.02, 0.04) (p = 0.026), where females had higher median ages than males. For the right mandibular third molar, significant differences between males and females were observed in the I3M groups [0.08, 0.3) (p = 0.021), [0.02, 0.04) (p = 0.006), and [0.00, 0.02) (p = 0.012), with females again showing higher median ages.

Table 2. Summary of descriptive statistics for chronological age (in years) and a comparison between males and females in each of third molar maturity index (I_{3M}) group for the left and right mandibular third molars (tooth 38 and 48)

I_{3M}	Male				Female				p-value[b]
	N	Mean ± SD (years)	Median (years)	p-value[a]	N	Mean ± SD (years)	Median (years)	p-value[a]	
Tooth 38									
[0.9,1.5)	3	14.64 ± 0.45	14.49	0.451	14	15.79 ± 1.44	15.72	0.066	0.200
[0.5,0.9)	16	14.86 ± 0.68	14.82	0.147	23	15.60 ± 1.28	15.37	0.025†	0.074
[0.3,0.5)	17	15.46 ± 0.87	15.37	0.456	24	16.40 ± 2.13	15.92	<0.001†	0.104
[0.08,0.3)	69	17.58 ± 1.92	17.23	<0.001†	64	18.10 ± 1.83	18.20	<0.001†	0.047*
[0.04,0.08)	39	19.33 ± 2.09	18.65	0.030†	40	20.56 ± 2.19	20.80	0.117	0.011*
[0.02,0.04)	30	20.48 ± 1.60	20.66	0.846	21	21.38 ± 1.56	21.48	0.013†	0.026*
[0.00,0.02)	58	21.44 ± 1.48	21.72	<0.001†	39	21.85 ± 1.32	21.88	0.262	0.190
Tooth 48									
[0.9,1.5)	5	14.88 ± 0.84	14.49	0.143	9	15.46 ± 1.22	15.68	0.295	0.365
[0.5,0.9)	16	14.90 ± 0.46	14.92	0.561	26	15.28 ± 1.05	14.96	0.015†	0.526
[0.3,0.5)	19	15.72 ± 1.12	15.75	0.575	18	16.47 ± 1.46	16.05	0.364	0.083
[0.08,0.3)	60	17.30 ± 1.86	16.99	<0.001†	65	18.18 ± 2.26	17.95	<0.001†	0.021*
[0.04,0.08)	30	19.42 ± 1.76	19.38	0.725	19	19.12 ± 1.57	19.09	0.389	0.546
[0.02,0.04)	25	19.33 ± 1.76	18.99	0.450	29	20.68 ± 2.08	20.88	0.012†	0.006*
[0.00,0.02)	71	21.48 ± 1.63	21.92	<0.001†	48	21.95 ± 1.46	22.18	0.012†	0.120

I3M third molar maturity index, *N* number of samples, *SD* standard deviation

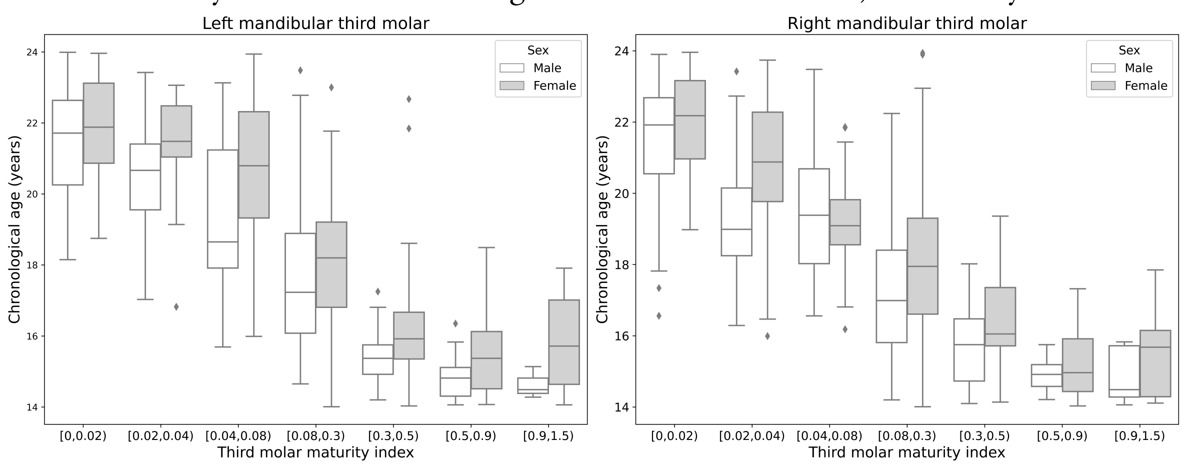
[a] p-value for normality test: Shapiro-Wilk test for N < 50; Kolmogorov-Smirnov test for N ≥ 50.

[b] p-value for comparing mean age between males and females: use an independent t-test if normality is met; otherwise, use the Mann-Whitney U test.

† p-value <0.05 indicates a significant deviation from normality, suggesting that the data is not normally distributed.

* p-value <0.05 indicates a statistically significant difference.

Figure 5. Boxplot illustrating the relationship between chronological age and Cameriere's third molar maturity index of the left and right mandibular third molars, stratified by sex



In comparing the left and right mandibular third molars, Demirjian's developmental stages were found to be statistically different between the two sides, with the left side developing faster than the right side by 0.06 stage (p = 0.01). Additionally, there was a statistically significant difference in I_{3M} between the left and right sides, with I_{3M} of the left side being 0.01 higher than that of the right side ($p < 0.01$).

The performance of Demirjian's stages and I_{3M} for age group classification at the 18-year threshold is shown in Tables 3 and 4. Concerning accuracy, which reflects the overall correct classification, Demirjian Stage G and I_{3M} less than 0.08 appear to have the highest accuracy. However, in a legal context, a false positive is the worst-case scenario. Therefore, we aim to primarily focus on the specificity score. In all groups, Stage H and I_{3M} less than 0.02 achieve the highest specificity scores. The scores were 1.00, except for the right mandibular third molar of males, which demonstrates specificity scores of 0.97 and 0.96 for the prediction threshold at Stage H and I_{3M} less than 0.02, respectively.

Table 3. Performance of Demirjian's stage and third molar maturity index (I3M) in age group classification at 18-year threshold using left mandibular third molar

Sex	Threshold	Accuracy (95% CI)	Sensitivity (95% CI)	Specificity (95% CI)	PPV (95% CI)	NPV (95% CI)	LR+ (95% CI)	LR- (95% CI)	*p* (95% CI)
Male	Stage E	0.62 (0.55, 0.68)	1.00 (1.00, 1.00)	0.07 (0.02, 0.12)	0.60 (0.54, 0.67)	1.00 (1.00, 1.00)	1.08 (1.02, 1.14)	0.00 (0.00, 0.82)	0.62 (0.56, 0.68)
	Stage F	0.70 (0.64, 0.76)	1.00 (1.00, 1.00)	0.28 (0.19, 0.37)	0.66 (0.6, 0.73)	1.00 (1.00, 1.00)	1.39 (1.23, 1.58)	0.00 (0.00, 0.21)	0.68 (0.62, 0.74)
	Stage G	0.86 (0.82, 0.91)	0.84 (0.78, 0.9)	0.90 (0.83, 0.96)	0.92 (0.87, 0.97)	0.80 (0.72, 0.87)	8.05 (4.46, 14.54)	0.18 (0.12, 0.27)	0.92 (0.89, 0.96)
	Stage H	0.65 (0.59, 0.71)	0.40 (0.31, 0.48)	1.00 (1.00, 1.00)	1.00 (1.00, 1.00)	0.54 (0.47, 0.61)	NA	0.6 (0.53, 0.69)	1.00 (1.00, 1.00)
	I3M < 0.08	0.83 (0.78, 0.88)	0.82 (0.76, 0.89)	0.84 (0.77, 0.92)	0.88 (0.83, 0.94)	0.77 (0.69, 0.85)	5.27 (3.29, 8.44)	0.21 (0.14, 0.30)	0.89 (0.85, 0.93)
	I3M < 0.04	0.77 (0.71, 0.82)	0.62 (0.54, 0.71)	0.97 (0.93, 1.00)	0.97 (0.93, 1.00)	0.65 (0.57, 0.72)	20.00 (6.52, 61.38)	0.39 (0.31, 0.48)	0.97 (0.95, 0.99)
	I3M < 0.02	0.66 (0.6, 0.72)	0.43 (0.34, 0.51)	1.00 (1.00, 1.00)	1.00 (1.00, 1.00)	0.55 (0.48, 0.63)	NA	0.57 (0.50, 0.67)	1.00 (1.00, 1.00)
Female	Stage E	0.65 (0.59, 0.71)	1.00 (1.00, 1.00)	0.17 (0.09, 0.24)	0.62 (0.56, 0.69)	1.00 (1.00, 1.00)	1.20 (1.10, 1.32)	0.00 (0.00, 0.37)	0.65 (0.59, 0.72)
	Stage F	0.78 (0.72, 0.83)	0.97 (0.94, 1.0)	0.52 (0.42, 0.62)	0.73 (0.67, 0.80)	0.92 (0.85, 1.00)	2.00 (1.62, 2.47)	0.06 (0.02, 0.16)	0.76 (0.7, 0.81)
	Stage G	0.76 (0.70, 0.82)	0.66 (0.58, 0.74)	0.89 (0.83, 0.96)	0.90 (0.83, 0.96)	0.66 (0.58, 0.74)	6.28 (3.45, 11.44)	0.38 (0.29, 0.49)	0.91 (0.87, 0.95)
	Stage H	0.58 (0.51, 0.64)	0.27 (0.19, 0.35)	1.00 (1.00, 1.00)	1.00 (1.00, 1.00)	0.50 (0.43, 0.57)	NA	0.73 (0.66, 0.81)	1.00 (1.00, 1.00)
	I3M < 0.08	0.80 (0.75, 0.86)	0.72 (0.64, 0.79)	0.93 (0.87, 0.98)	0.93 (0.88, 0.98)	0.70 (0.62, 0.78)	9.71 (4.72, 19.97)	0.31 (0.23, 0.41)	0.94 (0.91, 0.97)
	I3M < 0.04	0.68 (0.62, 0.74)	0.45 (0.37, 0.54)	0.99 (0.97, 1.00)	0.98 (0.95, 1.00)	0.57 (0.49, 0.65)	43.12 (6.08, 305.71)	0.55 (0.47, 0.65)	0.99 (0.97, 1.00)
	I3M < 0.02	0.60 (0.53, 0.66)	0.30 (0.22, 0.38)	1.00 (1.00, 1.00)	1.00 (1.00, 1.00)	0.51 (0.44, 0.58)	NA	0.70 (0.63, 0.78)	1.00 (1.00, 1.00)

PPV positive predictive value, *NPV* negative predictive value, LR+ positive likelihood ratio, LR- negative likelihood ratio, *p* Bayes post-test probability, CI confidence interval
NA not applicable (LR+ was not applicable due to the calculation resulting in an infinite value)

Table 4. Performance of Demirjian's stage and third molar maturity index (I3M) in age group classification at 18-year threshold using right mandibular third molar

Sex	Threshold	Accuracy (95% CI)	Sensitivity (95% CI)	Specificity (95% CI)	PPV (95% CI)	NPV (95% CI)	LR+ (95% CI)	LR- (95% CI)	*p* (95% CI)
Male	Stage E	0.61 (0.55, 0.67)	1.00 (1.00, 1.00)	0.10 (0.04, 0.16)	0.59 (0.53, 0.66)	1.00 (1.00, 1.00)	1.11 (1.04, 1.19)	0.00 (0.00, 0.62)	0.63 (0.56, 0.69)
	Stage F	0.70 (0.64, 0.76)	1.00 (1.00, 1.00)	0.32 (0.22, 0.41)	0.66 (0.59, 0.72)	1.00 (1.00, 1.00)	1.46 (1.28, 1.67)	0.00 (0.00, 0.20)	0.69 (0.63, 0.75)
	Stage G	0.85 (0.81, 0.90)	0.88 (0.82, 0.93)	0.83 (0.75, 0.90)	0.87 (0.81, 0.93)	0.84 (0.76, 0.91)	5.04 (3.26, 7.81)	0.15 (0.09, 0.24)	0.88 (0.84, 0.92)
	Stage H	0.68 (0.62, 0.74)	0.46 (0.38, 0.55)	0.97 (0.94,	0.95 (0.9, 1.00)	0.58 (0.50, 0.66)	15.00 (4.87, 47.00)	0.56 (0.47, 0.66)	0.96 (0.93, 0.98)
	I3M < 0.08	0.83 (0.78, 0.88)	0.84 (0.78, 0.91)	0.82 (0.74, 0.89)	0.86 (0.80, 0.92)	0.80 (0.72, 0.88)	4.59 (3.01, 7.02)	0.19 (0.13, 0.29)	0.87 (0.83, 0.92)
	I3M < 0.04	0.77 (0.72, 0.82)	0.67 (0.59, 0.75)	0.90 (0.84, 0.96)	0.90 (0.84, 0.96)	0.68 (0.60, 0.76)	6.58 (3.61, 12.00)	0.37 (0.28, 0.47)	0.91 (0.87, 0.95)
	I3M < 0.02	0.71 (0.65, 0.77)	0.52 (0.44, 0.61)	0.96 (0.92, 1.00)	0.94 (0.89, 1.00)	0.61 (0.53, 0.68)	13.00 (4.84, 34.00)	0.50 (0.41, 0.60)	0.95 (0.92, 0.98)
Female	Stage E	0.63 (0.56, 0.69)	0.99 (0.98, 1.00)	0.13 (0.06, 0.20)	0.61 (0.54, 0.67)	0.92 (0.78, 1.00)	1.14 (1.05, 1.24)	0.06 (0.01, 0.47)	0.64 (0.58, 0.7)
	Stage F	0.78 (0.72, 0.83)	0.98 (0.96, 1.00)	0.50 (0.39, 0.60)	0.72 (0.66, 0.79)	0.96 (0.90,	1.95 (1.59, 2.39)	0.03 (0.01, 0.13)	0.75 (0.70, 0.81)
	Stage G	0.82 (0.77, 0.87)	0.76 (0.68, 0.83)	0.90 (0.84, 0.96)	0.91 (0.86, 0.97)	0.73 (0.65, 0.81)	7.64 (4.08, 14.00)	0.27 (0.20, 0.37)	0.92 (0.89, 0.96)
	Stage H	0.61 (0.54, 0.67)	0.32 (0.24, 0.4)	1.00 (1.00, 1.00)	1.00 (1.00, 1.00)	0.52 (0.45, 0.59)	NA	0.68 (0.61, 0.77)	1.00 (1.00, 1.00)
	I3M < 0.08	0.80 (0.74, 0.85)	0.72 (0.64, 0.8)	0.91 (0.85, 0.97)	0.92 (0.86, 0.97)	0.70 (0.62, 0.79)	8.14 (4.16, 16.00)	0.31 (0.23, 0.42)	0.93 (0.89, 0.96)
	I3M < 0.04	0.75 (0.69, 0.81)	0.59 (0.51, 0.68)	0.96 (0.91, 1.00)	0.95 (0.90,	0.64 (0.55, 0.72)	14.00 (5.12, 36.00)	0.43 (0.34, 0.53)	0.96 (0.93, 0.98)
	I3M < 0.02	0.65 (0.59, 0.71)	0.39 (0.30, 0.48)	1.00 (1.00, 1.00)	1.00 (1.00, 1.00)	0.55 (0.47, 0.62)	NA	0.61 (0.53, 0.71)	1.00 (1.00, 1.00)

PPV positive predictive value, *NPV* negative predictive value, LR+ positive likelihood ratio, LR- negative likelihood ratio, *p* Bayes post-test probability, CI confidence interval
NA not applicable (LR+ was not applicable due to the calculation resulting in an infinite value)

DISCUSSION

This study employed both the Demerjian's[19] and Cameriere's[11] methods for dental age estimation. The Demerjian method, commonly used among the Thai population,[7, 10] assesses age by grading tooth development stages. However, its subjective interpretation can lead to errors, particularly with minor developmental variations. Alternatively, the Cameriere method[11] offers greater objectivity by quantifying the distance of open apices in radiographs but requiring meticulous measurements and specialised expertise.

Minimising false identification of minors as adults is critical in age estimation.[20] Therefore, the specificity score should be regarded as the most crucial factor. Previous studies conducted in the Thai population indicated that individuals reaching Stage H of mandibular third molar development were undoubtedly over 18 years old, with a specificity of 1.00, although a sensitivity is reduced.[7] In our study, which is the first to use I_{3M} for adult age assessment among Thais, we found that an I_{3M} cutoff of less than 0.08 yielded lower specificity scores than Demirjian's Stage H.

We then proposed a cutoff at I_{3M} less than 0.02, which achieved specificity scores comparable to Demirjian's Stage H but with higher sensitivity. These results align with previous comparative study, which revealed that I_{3M} criteria achieve comparable specificity scores to Demirjian's developmental stage while providing higher sensitivity scores.[11] In addition, comparing age estimation methods across different populations, this study noted that the development of third molars in the Thai population differed from that of other ethnic groups, highlighting the influence of ethnicity on tooth development. Therefore, employing population-specific reference data is essential for accurate age estimation in various population groups.

Sex dimorphism in the timing of mandibular third molar development was observed in our study. Using Demirjian's method, we found earlier dental development in males at specific stages. These results partially align with previous studies in Brazilians,[21] Turks,[22] and Thais,[7] which found statistically significant differences in some developmental stages between sexes. However, they contradict studies in Southern Italian[23] and Peruvian populations,[24] which revealed no difference in developmental stages between the sexes. Notably, the latter two studies had smaller sample sizes (460 and 208 individuals, respectively) compared to the other studies, which employed samples ranging from 500 to 1,867 individuals. Considering investigation of I3M, unlike studies on Croatian,[25] Serbian,[26] Turkish,[22] and other multi-ethnic populations (Europe, Africa, Asia, and America)[27] that reported earlier development in males, we found no significant sex differences in mandibular third molar development using the I3M method. This aligns with research from Southern Italy,[28] Botswana,[29] Peru,[24] and Northern China.[30] Ethnicity might explain this inconsistency. Additionally, variations in how studies group I_{3M} values could be a factor. Our study, specifically focused on evaluating cut-off points below 0.08, further divided I_{3M} values into groups like [0,0.02) and [0.02,0.04). These groupings were lower than those used in other studies.

Our study compared the development of the left and right mandibular third molars. Using Demirjian's method, while the right side showed a slightly faster development rate (mean difference of 0.06 stages), this difference was not clinically significant, and both sides can be used interchangeably for age estimation when necessary. This finding aligns with previous research by Duangto et al.[7] and Caggiano et al.,[23] which state that there were no differences in developmental stage among the left and right mandibular third molars. However, the maturity index analysis revealed a slight asymmetry, with the left side having a higher mean value (0.01), indicating a wider or slower developing root apex compared to the right. This finding is consistent with the multi-ethnic analysis of Angelaokpoulos et al.,[27] who reported similar asymmetry in Asian populations but not in Europe, Africa, and America. Regarding the final results of adult age assessment, we suggest that, in females, both left and right mandibular third molars can be used, as both of them achieve a high Bayes' post-test probability value. However, in males, the left side is preferred as it achieves a higher post-test probability value.

While valuable for age estimation of adolescents and young adults using third molars, Demerjian's and Cameriere's methods have limitations. These limitations include the presence of teeth that are absent (agenesis), misaligned, or obscured by pathology. For instance, studies have reported that bilateral mandibular third molar agenesis (missing wisdom teeth) occurs in 4.1% of females and 5.4% of males, highlighting a significant portion of the population where these methods would not be applicable.[31] This highlights the need for alternative age estimation approaches in these cases. Other methods, such as assessing the visibility of root pulp in mandibular molars[32] or secondary dentine formation in mandibular premolars,[33] can be helpful, as these teeth can serve as substitutes for age estimation when mandibular third molars are absent. Besides, estimating age from clavicle bone development using computed tomography could be one alternative,[34] but it is important to note that this technique carries a much higher radiation dose compared to the panoramic radiograph typically used for dental age estimation.

This study has limitations inherent to its cross-sectional design. While it offers valuable findings in dental development at a single point in time, it cannot establish causal relationships between development stages and age. Ideally, a prospective observational study following individuals over time would provide a more accurate understanding of third molar development and allow for refinement of the I_{3M} cutoff point.

However, ethically obtaining repeated dental radiographs in healthy individuals is not feasible. Additionally, the sample representativeness is limited. Although the study aims to propose a population-specific reference for Thais, data collection occurred at a single centre in the southern region. Future studies should incorporate a more diverse sample population to strengthen the generality of the findings. Furthermore, artificial intelligence (AI) for age estimation from maxillofacial radiographs shows promise, offering performance comparable to human examiners. AI could be especially useful in cases like mass victim identification, decomposed bodies, and criminal investigations.[35] Further research applying AI to this method could provide significant benefits.

CONCLUSION

In conclusion, this study found that an I3M cutoff of <0.02 achieved high specificity and better sensitivity than Demirjian's Stage H method for adult age estimation in Thais. Slight asymmetries in third molar development were observed, with the left side developing faster and having higher I3M values. Both mandibular third molars performed similarly for females, while the left was preferred for males due to its higher post-test probability.

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