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Research article

Evaluation of four criteria in assessing third molar maturity for age estimation in Koreans

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ABSTRACT

Third molar maturity is one of the major criteria for estimating human age. This study aimed to determine the most suitable third molar maturity criteria for age estimation in Koreans. The correlation between chronological age and the Demirjian, Köhler, Liversidge, and Thevissen criteria was evaluated using 900 panoramic radiographs of patients aged 15–23 years. The four criteria were applied separately to measure third molar maturity on the same radiograph. The concordance rates between third molars within the same jaw and between jaws were calculated and tested using a paired *t*-test. Regression was performed to observe the relationship between age and the evaluated stages for each tested criterion. The Demirjian standard showed the lowest root mean square error (1.29 years for males, 1.30 years for females) and highest adjusted R^2 (0.753 for males, 0.739 for females) values; however, the differences of the values derived from other criteria were minute. In addition, the symmetry (within the same jaw) and asymmetry (between the upper and lower jaws) of third molar development, which was confirmed in previous Korean studies, was observed only in the Demirjian and Liversidge criteria. Based on the results, we can conclude that all four tested criteria are suitable for age estimation in Koreans. However, the Demirjian and Liversidge criteria can be recommended from the perspective of accurate reflection of the developmental patterns. Further research is necessary to determine whether the results of this study are consistently observed in other populations.

1. Introduction

Tooth development is a continuous process that starts with tooth crown calcification and ends with the apical closure of the root. Because tooth development is under genetic control, differences in the timing and pace of tooth formation in an individual are low [1]. Therefore, many studies have attempted to estimate the dental age of an individual or evaluate the maturity of the body using tooth development, and satisfactory results have been reported. Therefore, dental growth and development has been applied in many fields of medical science, such as forensic medicine and pediatrics. The accuracy of dental age estimation for adults, which uses degenerative changes in teeth, tends to be lower than that for children, which uses dental development [2,3].

It is necessary to establish the evaluation criteria for tooth growth based on the anatomical and morphometric changes during development, to facilitate precise comparison between dental development and chronological age. However, the division of the

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developmental process into stages is inherently deficient for the accurate representation of dental development because it is a continuous process. If an evaluation system for dental development reflects the growth pattern more precisely, the accuracy of age estimation using that system could also increase. Several evaluation systems for teeth growth have been reported, and many scientific studies using these systems have been conducted for various populations. Gleiser and Hunt presented 15 stages of dental evaluation criteria to investigate the developmental pattern of the mandibular first molar [4]. The evaluation criteria by Gleiser and Hunt were modified by several researchers. Moorrees et al. [5] simplified the Gleiser and Hunt criteria for multi-rooted teeth and proposed a standard for single-rooted teeth [4]. Köhler (KHL) et al. presented a new standard that simplified the Gleiser and Hunt criteria into three crown stages and seven root stages in a study evaluating the growth of third molars in a German population [6]. Nolla presented a 10-stage scheme for tooth growth [7]. Among all the evaluation criteria listed above, tooth maturity was expressed in a fractional form with the presumed crown or root length at the time of evaluation. Demirjian (DMJ) et al. highlighted the subjectivity of these standards, which originated from presumed dental development and age estimation with lesser accuracy based on these standards [8]. They proposed a new system that uses the evaluation criteria that are visualized directly on radiographs only, such as the anatomical changes or the measurement values of teeth, to eliminate subjective evaluation factors. The DMJ evaluation criteria have since been applied by many researchers to population studies to observe the developmental patterns of teeth.

The third molar is the only tooth in the human dentition whose total chronology can be observed from the beginning of crown formation to root apex closure on medical images acquired for clinical use. Therefore, the third molar is frequently used to track chronological changes in tooth growth. Since the legal threshold age of the majority of the population lies within the maturity span of these teeth, many scientific methods have been devised for estimating the legal age threshold using third molar development. In reported third molar development studies, the DMJ [9–17] or KHL criteria [18–22] were frequently used as evaluation systems for dental development. Meanwhile, some methods entail quantitative evaluation using measured values instead of scoring for development evaluation. Cameriere et al. proposed the third molar maturity index (I3M), which is a quantitative method for age estimation [23], which is considered suitable and reliable in forensic settings in different ethnic populations [24].

Attempts to modify conventional standards for improving the accuracy of dental age estimation have also been reported. Because the growth span of the third molar root is longer than that of other permanent teeth, Solari and Abramovitch presented modified criteria that subdivided DMJ stages (F and G stages) for root evaluation, and applied age estimation to Hispanic Americans [25]. They argued that these two additional stages may improve accuracy, especially when calculating the probability of an individual being a minor. Thevissen (TVS) et al. modified the KHL criteria to compensate for the shortcomings resulting from the use of assumed estimates of length in the evaluation [26]. They measured the vertical line from the cementoenamel junction to the tooth apex of the second and third molars, calculated the ratio of the measured values of the vertical lines between the second and third molars, and determined the developmental stages of the third molars according to this ratio. For example, if this ratio is calculated to be 0.51, the observed third molar is evaluated as stage 6 according to the KHL criteria (complete 1/2 of the tooth root). Liversidge (LVD) presented a new standard based on Moorrees' criteria by adding descriptive reference points composed of anatomical features to aid the observer in determining the stage at each evaluation point [27].

Population studies using third molar chronology in Koreans and relevant age estimation methods have already been reported [9, 10]. However, all previous studies on the Korean population evaluated the development status of third molars using the DMJ criteria, and no study applied the Gleiser and Hunt system or other modified criteria, such as the KHL or Moorrees' criteria. This study aimed to identify the most suitable criteria for evaluating third molar development in the Korean population. For this purpose, third molar development status was evaluated on the same radiograph collected from a Korean population using the DMJ and KHL criteria, which were mainly used in previous population studies, and the statistical correlations were analyzed. In addition, the TVS and LVD criteria, which were recently modified to enhance the accuracy of dental age estimation, were also investigated. We compared the correlation between each criterion and chronological age and attempted to suggest the most appropriate developmental system for age estimation in the Korean population.

Table 1
Distribution of age and sex of the samples.

	Male			Female			Total		
Age (years)	N	Mean	SD	N	Mean	SD	n	Mean	SD
15.00–15.99	50	15.56	0.25	50	15.53	0.29	100	15.55	0.27
16.00–16.99	50	16.52	0.30	50	16.49	0.27	100	16.51	0.28
17.00–17.99	50	17.55	0.32	50	17.53	0.31	100	17.54	0.31
18.00–18.99	50	18.49	0.30	50	18.54	0.29	100	18.51	0.30
19.00–19.99	50	19.42	0.27	50	19.44	0.31	100	19.43	0.29
20.00–20.99	50	20.54	0.29	50	20.53	0.30	100	20.54	0.30
21.00–21.99	50	21.52	0.31	50	21.52	0.31	100	21.52	0.31
22.00–22.99	50	22.56	0.25	50	22.52	0.29	100	22.54	0.27
23.00–23.99	50	23.46	0.30	50	23.50	0.26	100	23.48	0.28
Total	450	19.51	2.59	450	19.51	2.60	900	19.51	2.59

SD, standard deviation.

2. Materials and methods

The sample size estimation was based on a multiple linear regression considering three predictors, with a confidence level of 95% and statistical power of 80. Assuming that the effect size f^2 was small ($f^2 = 0.03$), the sample size was calculated to be 325 using G*Power software (Dusseldorf, Germany). The final sample size included 900 panoramic radiographs of 450 Korean males and 450 females. The study participants aged between 15 and 23 years, were randomly selected and stratified by sex, and were enrolled from The Catholic University of Korea at St. Mary's Hospital, Yonsei University Dental Hospital, and Seoul National University Dental Hospital. The chronological age of the radiographs was calculated by subtracting the date of the radiograph from the date of birth. All radiographs were obtained for clinical use, and the related medical records were reviewed retrospectively to exclude patients with a history of systemic disease or orofacial injuries that may affect tooth development. Radiographs depicting at least one third molar were selected, and those showing advanced dental caries, endodontically filled root canals, pathological bony lesions around the third molar, and unclear or blurred images of third molars were excluded. The age and sex distribution of the study sample are presented in Table 1. The number of participants assigned to each stage was equally distributed. This study was approved by the Institutional Review Board (IRB) of Seoul St. Mary's Hospital, Catholic University of Korea (approval no.: KC22WISI0329).

The degree of development of 2940 third molars were staged and scored on the orthopantomograms, according to the dental evaluation systems devised by DMJ [8], KHL [6], TVS [26] and LVD [27]. The staging criteria for each system are presented in Supplementary Figures S1, S2, S3 and S4. Table 2 shows the number of stages in each system and the classification of stages according to the tooth anatomy. The assumption of normality was checked using the Shapiro–Wilk test for continuous variables. The baseline characteristics of the population are expressed as means ± standard deviations or medians, including interquartile range. Ninety randomly selected radiographs (10% of the total study sample) were evaluated by two experienced observers to test the inter-observer reliability, and twice by the main observers, at an interval of two months, to test the intra-observer reliability. Pearson's correlations were calculated to explore the association between chronological age and developmental stages of third molars stratified by sex. To investigate how well each criterion reflects the possible differences in the development of third molars, the difference between the left and right and the upper and lower teeth was tested using the paired *t*-test to observe statistically significant differences. Univariable regressions were performed to observe the relationship between chronological age and each stage evaluated with the four criteria of the left and right third molars in both jaws. Multivariable regression analyses were performed using combinations of maxillary and mandibular third molars. Regression models were also generated using log-transformed variables based on normality. The final regression model with four third molars in the entire dentition as variables was calculated using backward elimination procedures. The performance of each model was compared using adjusted R^2 and root mean square error (RMSE). Statistical significance was defined as a two-tailed *P*-value of <0.05. All data analyses were performed using SAS version 9.4 (SAS Institute Inc., Cary, NC, USA).

3. Results

The descriptive statistics for the development of the four third molars according to each evaluation criterion stage are expressed in the Supplementary Tables and Figures. The kappa values for intra-observer reliability were 0.981, 0.972, 0.978 and 0.98 for the DMJ, KHL, TVS and LVD criteria, respectively. The kappa values for interobserver reliability were 0.972, 0.909, 0.946 and 0.966 for the DMJ, KHL, TVS and LVD criteria, respectively. The 95% confidence intervals of kappa values are presented in Supplementary Table S5. The kappa values were construed as "almost perfect," consistent with the Landis and Koch standard [28]. The concordance rate of the evaluated stages between the third molars in the same jaw showed no statistically significant difference in any criterion, except for the KHL stages between the upper third molars of females ($P < 0.05$). The concordance rate of the stages between the upper and lower third molars was statistically significant ($P < 0.05$) in both sexes and both sides according to the DMJ and LVD criteria. However, there was no statistically significant difference in the stages between the right maxillary and mandibular third molars of males according to the KHL, and TVS criteria. There was no significant difference in the KHL and TVS criteria between the left third molars of both jaws in males and between the right third molars of females (Table 3). The developmental symmetricity between the third molars within the jaw or between the jaws was evaluated using each criterion (Table 4), based on the statistical significance of the concordance rate between the evaluated stages of the third molars ($P < 0.05$). Pearson's correlation coefficients between the stages and age showed a very high positive correlation (over 0.80 in all third molars of both sexes) in all the evaluated criteria [29]. The lowest correlation (0.802) was observed in the LVD stages of the mandibular left third molar in males and the highest correlation (0.858) was observed in the DMJ stages of the maxillary right third molar in females (Table 5). As a result of univariable regression for each stage of the four

Table 2
The number of stages of each tested criteria for maturity evaluation of different tooth parts.

		Tooth criteria			
		DMJ	KHL	TVS	LVD
Tooth part	Crypt				1
	Crown	4	3	3	6
	Root	3	5	5	6
	Apex	1	2	2	2
Total		8	10	10	15

DMJ, Demirjian; KHL, Köhler; TVS, Thevissen; LVD, Liversidge.

Table 3
Concordance rate of maturity scores between third molars within the same jaw and between jaws.

Criteria	Teeth	Male		Female	
		Concordance Rate (%)	*P*-value	Concordance Rate (%)	*P*-value
DMJ	UR-UL	91.3	0.494	86.7	0.286
	LR-LL	91.0	0.739	89.6	0.170
	UR-LR	75.0	0.002*	69.3	0.000*
	UL-LL	80.7	0.006*	65.9	0.000*
KHL	UR-UL	79.6	0.584	75.6	0.002*
	LR-LL	80.1	0.127	78.2	0.201
	UR-LR	61.8	0.945	56.5	0.393
	UL-LL	63.8	0.666	54.9	0.000*
TVS	UR-UL	84.4	0.116	68.8	0.080
	LR-LL	86.2	0.061	72.4	0.683
	UR-LR	63.0	0.664	52.0	0.062
	UL-LL	65.7	0.277	47.1	0.002*
LVD	UR-UL	78.8	0.447	76.5	0.389
	LR-LL	80.2	0.618	72.6	0.834
	UR-LR	58.1	0.047*	52.7	0.000*
	UL-LL	64.9	0.010*	52.6	0.000*

UR, upper right third molar score; UL, upper left third molar score; LL, lower left third molar score; LR, lower right third molar score; DMJ, Demirjian; KHL, Köhler; TVS, Thevissen; LVD, Liversidge; $^*P < 0.05$ indicates a statistically significant difference.

Table 4
The developmental symmetricity of the third molars within the jaw or between jaws, which varied according to each criterion.

Criteria	Male				Female			
	UR-UL	LR-LL	UR-LR	UL-LL	UR-UL	LR-LL	UR-LR	UL-LL
DMJ	Sym	Sym	Asym	Asym	Sym	Sym	Asym	Asym
KHL	Sym	Sym	Sym	Sym	Asym	Sym	Sym	Asym
TVS	Sym	Sym	Sym	Sym	Sym	Sym	Sym	Asym
LVD	Sym	Sym	Asym	Asym	Sym	Sym	Asym	Asym

UR, upper right third molar score; UL, upper left third molar score; LL, lower left third molar score; LR, lower right third molar score; DMJ, Demirjian; KHL, Köhler; TVS, Thevissen; LVD, Liversidge; Sym, symmetry; Asym, asymmetry.

Table 5
Pearson's correlation coefficients between chronological age and developmental scores of third molars.

Criteria	Tooth	Male	Female
DMJ	UR	0.848	0.864
	UL	0.848	0.858
	LL	0.845	0.835
	LR	0.856	0.842
KHL	UR	0.846	0.839
	UL	0.843	0.839
	LL	0.843	0.833
	LR	0.847	0.837
TVS	UR	0.842	0.831
	UL	0.841	0.837
	LL	0.843	0.827
	LR	0.850	0.831
LVD	UR	0.809	0.839
	UL	0.809	0.846
	LL	0.802	0.823
	LR	0.807	0.829

UR, upper right third molar score; UL, upper left third molar score; LL, lower left third molar score; LR, lower right third molar score; DMJ, Demirjian; KHL, Köhler; TVS, Thevissen; LVD, Liversidge.

third molars (Table 6), the RMSE (1.33–1.41 years) and adjusted R^2 (0.707–0.733) of the DMJ, KHL, and TVS criteria were similarly observed for all teeth in males, whereas, for the LVD criteria, the RMSE was 0.22 years higher, and the adjusted R^2 was 0.09 lower. Based on the RMSE and adjusted R^2 of the univariable regression for third molars in females, the DMJ criteria were more accurate than the other criteria; however, the differences in RMSE and adjusted R^2 between the four criteria were much smaller than those for third molars in males (Table 6). The DMJ criteria appeared to be the most appropriate among the tested criteria for both sexes with respect to the RMSE and adjusted R^2 of multivariable regressions for third molars within the same jaw (Table 7). Furthermore, the DMJ criteria

Table 6
Regression formulae for each criterion according to the developmental score of the third molar.

	Male						Female					
Criteria	Regression formula				RMSE	Adj. R^2	Regression formula				RMSE	Adj. R^2
DMJ	Age =	7.2302	+	(UR × 1.8343)	1.37	0.718	Age =	9.3674	+	(UR × 1.6434)	1.30	0.746
	Age =	7.2584	+	(UL × 1.8454)	1.38	0.717	Age =	9.2323	+	(UL × 1.6550)	1.33	0.736
	Age =	7.0177	+	(LL × 1.9064)	1.39	0.713	Age =	10.1448	+	(LL × 1.5568)	1.40	0.697
	Age =	6.9967	+	(LR × 1.9109)	1.33	0.733	Age =	9.9950	+	(LR × 1.5816)	1.39	0.707
KHL	Age =	10.9286	+	(UR × 1.0693)	1.38	0.714	Age =	11.9463	+	(UR × 1.0401)	1.41	0.702
	Age =	10.9257	+	(UL × 1.0779)	1.40	0.709	Age =	11.5842	+	(UL × 1.0716)	1.42	0.703
	Age =	10.6508	+	(LL × 1.1185)	1.39	0.709	Age =	12.3009	+	(LL × 1.0042)	1.41	0.694
	Age =	10.5873	+	(LR × 1.1228)	1.38	0.716	Age =	11.7465	+	(LR × 1.0700)	1.41	0.700
TVS	Age =	11.2147	+	(UR × 1.0420)	1.40	0.708	Age =	12.2731	+	(UR × 1.0122)	1.44	0.690
	Age =	11.4704	+	(UL × 1.0210)	1.41	0.707	Age =	11.9570	+	(UL × 1.0392)	1.43	0.699
	Age =	11.4827	+	(LL × 1.0280)	1.39	0.709	Age =	12.7951	+	(LL × 0.9571)	1.44	0.683
	Age =	11.3122	+	(LR × 1.0444)	1.36	0.721	Age =	12.3103	+	(LR × 1.0192)	1.43	0.690
LVD	Age =	7.8067	+	(UR × 0.9187)	1.52	0.653	Age =	9.2462	+	(UR × 0.8627)	1.41	0.702
	Age =	7.5430	+	(UL × 0.9431)	1.53	0.654	Age =	9.2249	+	(UL × 0.8596)	1.38	0.715
	Age =	7.1827	+	(LL × 0.9837)	1.55	0.643	Age =	10.1019	+	(LL × 0.8055)	1.44	0.677
	Age =	7.1486	+	(LR × 0.9868)	1.53	0.650	Age =	10.0657	+	(LR × 0.8059)	1.44	0.686

UR, upper right third molar score; UL, upper left third molar score; LL, lower left third molar score; LR, lower right third molar score; DMJ, Demirjian; KHL, Köhler; TVS, Thevissen; LVD, Liversidge; RMSE, root mean square error; Adj. R^2, adjusted R^2; all P-values were less than 0.001 ($P < 0.001$).

were also the most appropriate in multiple regression analysis considering the third molars of the upper and lower jaws for both sexes; the RMSE and adjusted R^2 decreased in following order: KHL, TVS, and LVD in males, and LVD, KHL, and TVS in females (Table 8 and Fig. 1). The performance of regression models that incorporated log-transformed variables was lower than that of regression models with continuous variables in all tested criteria (Table 9). The mean estimated dental age and the mean difference between the chronological and dental ages for each criterion are reported in Tables 10 and 11.

4. Discussion

We analyzed the relationship between the evaluated stages with each criterion and chronological age by applying four criteria (DMJ, KHL, TVS, and LVD) to the same panoramic radiograph of Korean individuals. Based on the results, we determined the most suitable criterion for third molar-based age estimation in the Korean population. According to multiple regression analysis, the correlation between the maturity of the four third molars and age and the DMJ system was the most appropriate for both males and females. In the male population, the DMJ showed the best performance, while the LVD showed the worst performance, with a small difference of 0.19 years as evidenced by the RMSE values of the four criteria. In females, the difference was even smaller, with the RMSE only increased with 0.09 year using the worst criteria (TVS) compared to the DMJ. The maximal difference between the adjusted R^2 values between the best and worst criteria was 7.6% for the male population and 3.1% for the female population. These minute differences were not evident in the results. Therefore, the results of this study, which suggest that the DMJ system is the most suitable for age estimation in Koreans, should be considered carefully, even though the DMJ criteria exhibited the lowest RMSE and highest adjusted R^2 values.

Thevissen et al. evaluated the correlations between nine registration techniques for evaluating third molar tooth maturity and chronological age using regression analysis [30]. They reported that the difference in R^2 between the most and least accurate methods was only 7.4% and 5.8% for males and females, respectively. They asserted that these differences were clinically insignificant, even though they were statistically significant. Liversidge evaluated the development of the mandibular second molar using the DMJ and Moorrees staging techniques and compared the performance of each reference data [31]. Although she found that the Moorrees scoring system was marginally better, she decided that both systems were suitable for age estimation. The author asserted that the selection between them was a personal choice that depended on the presence of reference data feasible to the examiner. Rodriguez et al. also tested the performance of 12 age estimation methods based on their accuracy and precision for the Mexican population [32]. They reported that the Willems method, which relies on the DMJ criterion, was the most accurate by comparing the mean residual and mean of the absolute value of residual and argued that the conclusion for suitability of which method was the best should be cautiously interpreted because of small differences in mean residual and mean of the absolute value of residual. The findings of previous studies [30–32] are consistent with the results of this study. Therefore, when estimating age using third molar maturity in Koreans, it can be concluded that all the criteria tested in this study are suitable from a practical point of view.

In this study, the DMJ was the most suitable system for both sexes, followed by the KHL, TVS, and LVD in males and LVD, KHL, and TVS in females, in ascending order of RMSE. This may be attributed to the fact that the staging criteria of the DMJ registration technique are different from those of the other tested techniques. The DMJ criterion uses only observable anatomical indicators on radiographs to evaluate maturity, which makes staging more objective. However, when evaluating growth using the KHL or TVS criterion, tooth maturity is expressed in the fractional form after comparing the observed development of the crowns or roots of the teeth with the predicted final growth. As the principal staging standards of the KHL or TVS criterion depend on the observer's subjective prediction, these criteria might be more inaccurate than the DMJ. Olze et al. validated five different evaluation systems for the

Table 7
Regression formulae for each system according to the developmental score of third molars within the same jaw.

	Male			Female		
Criteria	Regression formula	RMSE	Adj. R^2	Regression formula	RMSE	Adj. R^2
DMJ	Age = 6.4414 + (UR × 0.9750) + (UL × 0.9733)	1.31	0.744	Age = 8.9117 + (UR × 1.0534) + (UL × 0.6513)	1.26	0.764
KHL	Age = 10.5118 + (UR × 0.7281) + (UL × 0.3872)	1.34	0.730	Age = 11.4052 + (UR × 0.5823) + (UL × 0.5150)	1.37	0.724
TVS	Age = 10.9477 + (UR × 0.7682) + (UL × 0.3028)	1.36	0.725	Age = 11.6990 + (UR × 0.5764) + (UL × 0.4997)	1.37	0.723
LVD	Age = 6.6060 + (UR × 0.5422) + (UL × 0.4652)	1.42	0.696	Age = 8.7374 + (UR × 0.4355) + (UL × 0.4629)	1.33	0.737
DMJ	Age = 6.5865 + (LL × 0.4229) + (LR × 1.5449)	1.32	0.739	Age = 9.7264 + (LL × 0.6788) + (LR × 0.9443)	1.35	0.717
KHL	Age = 10.2914 + (LL × 0.3764) + (LR × 0.7817)	1.34	0.730	Age = 11.7638 + (LL × 0.4828) + (LR × 0.5846)	1.38	0.708
TVS	Age = 11.1369 + (LL × 0.2376) + (LR × 0.8271)	1.34	0.730	Age = 12.2561 + (LL × 0.4073) + (LR × 0.6183)	1.39	0.705
LVD	Age = 6.4973 + (LL × 0.3582) + (LR × 0.6769)	1.50	0.663	Age = 9.7217 + (LL × 0.4106) + (LR × 0.4234)	1.40	0.697

UR, upper right third molar score; UL, upper left third molar score; LL, lower left third molar score; LR, lower right third molar score; DMJ, Demirjian; KHL, Köhler; TVS, Thevissen; LVD, Liversidge; RMSE, root mean square error; Adj. R^2, adjusted R^2; all P-values were less than 0.05 ($P < 0.05$).

Table 8
Regression formulae for each system according to the developmental score of the maxillary and mandibular third molars.

Criteria	Male: Regression formula	Male: RMSE	Male: Adj. R^2	Female: Regression formula	Female: RMSE	Female: Adj. R^2
DMJ	Age = 6.6460 + (U × 1.0052) + (L × 0.9464)	1.29	0.753	Age = 9.1701 + (U × 1.0716) + (L × 0.6154)	1.30	0.739
KHL	Age = 10.4479 + (U × 0.5486) + (L × 0.5916)	1.35	0.730	Age = 11.7004 + (U × 0.5428) + (L × 0.5324)	1.38	0.711
TVS	Age = 11.2228 + (U × 0.5084) + (L × 0.5490)	1.36	0.726	Age = 12.1108 + (U × 0.5487) + (L × 0.4918)	1.39	0.708
LVD	Age = 6.8777 + (U × 0.4729) + (L × 0.5292)	1.48	0.677	Age = 9.0685 + (U × 0.5103) + (L × 0.3729)	1.34	0.723

U, upper third molar score; L, lower third molar score; DMJ, Demirjian; KHL, Köhler; TVS, Thevissen; LVD, Liversidge; RMSE, root mean square error; Adj. R^2, adjusted R^2; all P-values were <0.001 ($P < 0.001$). If the same type of teeth are found on both sides of the same jaw, only one tooth with a lower stage should be selected [9,10].

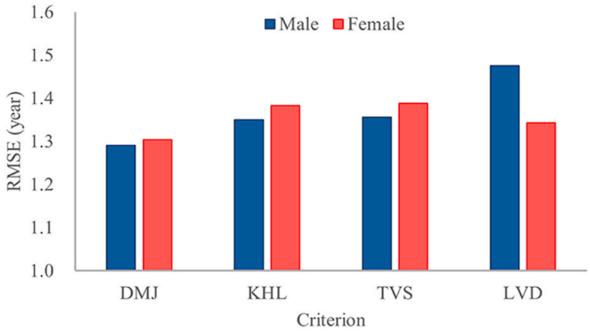

Fig. 1. Root mean square error (RMSE) for each tested criteria based on the upper and lower third molar scores. DMJ, Demirjian's criterion; KHL, Köhler's criterion; TVS, Thevissen's criterion; LVD, Liversidge's criterion.

third molars and reported that the DMJ criterion was superior with respect to both inter-observer reliability and correlation with chronological age because it does not define speculative estimated length as a standard basis [33].

Although the LVD criteria originate from the Moorrees system, they are similar to the DMJ with respect to the clarity of the descriptive criteria used for staging. Therefore, the correlation between the LVD system and age is expected to be higher than that of the KHL and TVS. In females, as expected, better performance was observed for LVD than for KHL or TVS, and the RMSE difference from the DMJ, which was observed to be the most appropriate, was only 0.04 years. However, the RMSE was 0.19 years in the male population, which was four times greater than that in the female population, which was the worst performance among the tested criteria. In this study, the lower correlation between the LVD system and age compared to that between the DMJ and age is attributed to the over-subdivided and over-nested stages. If each stage is divided too finely and the thresholds of each stage are close, classification (into a given stage) becomes more difficult and the probability of misclassification increases. As there are currently no population studies or comparative studies on the LVD system, it is necessary to carefully infer whether the sexual dimorphism for LVD accuracy observed in this study is Korean population-specific. Future studies with more samples or cross-comparison studies using other population data are required.

The TVS criteria were modified from the KHL criteria to compensate for inherent limitations, such as the subjective estimation of the fraction. In performing age estimation with the TVS criteria, third molar maturity is assessed with reference to the two measured values from the second molar. This implies that an extra process is added when estimating age with TVS compared with KHL. Both systems showed a higher RMSE value than that of the DMJ; the RMSE of the TVS was slightly higher than that of the KHL. These results suggest that modifications in the TVS system do not make a significant contribution to improving age estimation accuracy and applying KHL might be more efficient than TVS in forensic practice.

Although tooth maturity is known to be symmetrical in general, both within the same jaw and between the jaws [34], several studies have reported statistically significant differences between the maxilla and mandible in the case of the third molar [9,11–17,35]. Similar results were also reported by previous population studies of third molar maturity in Koreans [9,10]. In this study, no side differences or statistically significant arch differences were observed for the DMJ and LVD criteria ($P < 0.05$). However, atypical results were observed for KHL and TVS, such as statistically significant side differences (KHL in the female population; $P < 0.05$) or no significant arch differences (KHL and TVS in both sexes; $P < 0.05$). The variations in the results were also attributed to the objectivity of the staging system, which originated from the descriptive criteria. This implies that assessment of tooth development with the DMJ and LVD is less prone to error when used in Koreans. Future studies using data from other populations will validate the results of this study.

In this study, RMSE and adjusted R^2 were used as indices to evaluate the performance of different systems. However, several studies have evaluated the performance of a system with reproducibility by analyzing the inter- or intra-observer reliability. In general, as the number of stages of the evaluation standard decreases, reproducibility increases, but it can be predicted that the performance of measuring the dental maturity of the standard will deteriorate. Thevissen et al. [30] asserted that the number of stages contained in the standard and accuracy of the classification performance were inversely proportional. Dhanjal et al. [36] tested the reproducibility of four systems for the evaluation of third molars and suggested that the DMJ is the first choice of recommendation. They listed a clear definition of the criteria and fewer intermediate stages as reasons for the higher reproducibility of the DMJ. Jayaraman et al. [37] made a similar claim in a comparative study of the DMJ and Moorrees' systems in Hispanic children. We also observed the highest reproducibility of the DMJ criteria with respect to the inter- and intra-observer reliability. However, since we calculated the reliability for only 10% of the total sample, direct comparison with the results of previous studies is possibly erroneous. Follow-up studies testing inter- and intra-observer reliability of the four criteria should be conducted to confirm whether the results of this study can be similarly reproduced.

Radiological methods used to estimate of the ages of living individuals with third molars should conform to the as-low-as reasonably achievable, i.e., ALARA, principle [38]. The radiographic exposure in panoramic radiography or CT can be classified as a negligible risk [39]. The effective dose from panoramic radiography is 0.02 mSv, which is equivalent to three days of background radiation, and is even less than that with intraoral X-rays [40]. However, the European Asylum Support Office recommends that non-medical methods should be applied first and medical methods should be used only if doubts remain, even though the error ranges of radiological methods are better known, tested, and quantifiable than those of non-medical methods [41]. According to recent

Table 9
Regression formulae for each system according to the log-transformed developmental scores of the maxillary and mandibular third molars.

	Male								Female							
Criteria	Regression formula						RMSE	Adj. R^2	Regression formula						RMSE	Adj. R^2
DMJ	Age =	−3.1425	+	(U × 4.3492)	+	(L × 7.7098)	1.36	0.721	Age =	2.4235	+	(U × 6.5867)	+	(L × 2.9599)	1.37	0.710
KHL	Age =	3.6386	+	(U × 3.8114)	+	(L × 3.9171)	1.46	0.678	Age =	4.8910	+	(U × 4.2196)	+	(L × 3.2858)	1.45	0.680
TVS	Age =	4.0453	+	(U × 4.2248)	+	(L × 3.3579)	1.38	0.710	Age =	5.5987	+	(U × 4.0034)	+	(L × 3.2416)	1.45	0.682
LVD	Age =	−8.5954	+	(U × 4.6339)	+	(L × 6.4872)	1.57	0.627	Age =	−3.2768	+	(U × 5.7778)	+	(L × 3.5287)	1.47	0.667

U, upper third molar score; L, lower third molar score; DMJ, Demirjian; KHL, Köhler; TVS, Thevissen; LVD, Liversidge; RMSE, root mean square error; Adj. R^2, adjusted R^2; all *P*-values were <0.001 ($P < 0.001$). If the same type of teeth are found on both sides of the same jaw, only one tooth with a lower stage should be selected [9,10].

Table 10
Mean difference between the chronological and estimated dental ages according to sex, age group, and criterion.

	Male							
	DMJ		KHL		TVS		LVD	
Age (years)	DA	CA-DA	DA	CA-DA	DA	CA-DA	DA	CA-DA
15.00–15.99	16.42	−0.87	16.18	−0.66	16.45	−0.92	16.37	−0.82
16.00–16.99	17.20	−0.65	17.29	−0.74	17.04	−0.49	17.47	−0.92
17.00–17.99	17.88	−0.32	17.76	−0.21	17.76	−0.21	18.19	−0.63
18.00–18.99	18.32	0.16	18.63	−0.13	18.45	0.05	18.63	−0.15
19.00–19.99	19.57	−0.16	20.07	−0.66	19.97	−0.56	19.74	−0.33
20.00–20.99	20.15	0.39	20.65	−0.10	20.92	−0.37	19.93	0.61
21.00–21.99	21.63	−0.08	21.35	0.18	21.34	0.19	21.35	0.20
22.00–22.99	22.12	0.44	21.71	0.85	21.73	0.83	21.76	0.80
23.00–23.99	21.90	1.54	21.64	1.80	21.61	1.83	21.67	1.77
	Female							
	DMJ		KHL		TVS		LVD	
Age (years)	DA	CA-DA	DA	CA-DA	DA	CA-DA	DA	CA-DA
15.00–15.99	16.29	−0.77	16.70	−1.16	16.94	−1.40	16.26	−0.74
16.00–16.99	17.33	−0.82	17.49	−0.98	17.42	−0.91	17.22	−0.71
17.00–17.99	18.23	−0.67	18.10	−0.52	18.21	−0.63	18.31	−0.75
18.00–18.99	18.79	−0.25	18.95	−0.43	18.66	−0.14	19.04	−0.50
19.00–19.99	19.48	−0.04	19.31	0.14	19.37	0.08	19.70	−0.26
20.00–20.99	20.06	0.48	20.45	0.09	20.52	0.02	20.26	0.28
21.00–21.99	20.88	0.64	20.58	0.96	20.42	1.12	20.76	0.76
22.00–22.99	22.12	0.37	22.02	0.48	22.02	0.48	21.90	0.59
23.00–23.99	22.56	0.98	22.35	1.20	22.34	1.21	22.27	1.27

DMJ, Demirjian's criterion; KHL, Köhler's criterion; TVS, Thevissen's criterion; LVD, Liversidge's criterion; CA, mean of chronological age; DA, mean of estimated dental age; CA-DA, mean difference between chronological and estimated dental age.

Table 11
Mean difference between chronological age and estimated dental age with formulae derived from log-transformed variables according to sex, age group, and criterion.

	Male							
	DMJ		KHL		TVS		LVD	
Age (years)	DA	CA-DA	DA	CA-DA	DA	CA-DA	DA	CA-DA
15.00–15.99	16.41	−0.86	16.25	−0.73	16.41	−0.88	16.50	−0.95
16.00–16.99	17.25	−0.70	17.42	−0.87	17.14	−0.59	17.57	−1.02
17.00–17.99	18.09	−0.53	18.04	−0.49	17.94	−0.39	18.43	−0.87
18.00–18.99	18.55	−0.07	18.89	−0.39	18.66	−0.16	18.87	−0.39
19.00–19.99	19.71	−0.30	20.14	−0.73	20.05	−0.64	19.82	−0.41
20.00–20.99	20.19	0.35	20.60	−0.05	20.90	−0.35	19.93	0.61
21.00–21.99	21.41	0.14	21.11	0.42	21.18	0.35	21.08	0.47
22.00–22.99	21.84	0.72	21.40	1.16	21.51	1.05	21.42	1.14
23.00–23.99	21.65	1.79	21.34	2.10	21.42	2.02	21.35	2.09
	Female							
	DMJ		KHL		TVS		LVD	
Age (years)	DA	CA-DA	DA	CA-DA	DA	CA-DA	DA	CA-DA
15.00–15.99	16.12	−0.60	16.49	−0.95	16.73	−1.19	16.23	−0.71
16.00–16.99	17.44	−0.93	17.58	−1.07	17.45	−0.94	17.36	−0.85
17.00–17.99	18.45	−0.89	18.25	−0.67	18.31	−0.73	18.53	−0.97
18.00–18.99	19.02	−0.48	19.16	−0.64	18.84	−0.32	19.24	−0.70
19.00–19.99	19.69	−0.25	19.52	−0.07	19.51	−0.06	19.87	−0.43
20.00–20.99	20.18	0.36	20.50	0.04	20.57	−0.03	20.34	0.20
21.00–21.99	20.87	0.65	20.61	0.93	20.51	1.03	20.72	0.80
22.00–22.99	21.81	0.68	21.81	0.69	21.86	0.64	21.59	0.90
23.00–23.99	22.15	1.39	22.04	1.51	22.11	1.44	21.85	1.69

DMJ, Demirjian's criterion; KHL, Köhler's criterion; TVS, Thevissen's criterion; LVD, Liversidge's criterion; CA, mean of chronological age; DA, mean of estimated dental age; CA-DA, mean difference between chronological and estimated dental age.

studies, radiological methods for estimating molar maturity (viz. the DMJ, KHL, TVS, and LVD) should be applied in every age estimation process around the age limit of 18 years, which is in the best interest of the individual and can yield the best forensic outcome [39,42]. In this study, the superior accuracy of the DMJ over that of the other three criteria (KHL, TVS, and LVD) provides sufficient evidence of the utility of radiological methods to assess dental maturation and the risk of under or over-estimation of age.

5. Conclusion

In this study, the DMJ system was observed to be the most appropriate in the male and female populations. Since the RMSE of the tested criteria shows only a slight difference, all four criteria are suitable for forensic age estimation using third molar maturity in Koreans. However, since there are differences in the accuracy of estimation and in the reflection of growth patterns between criteria, forensic experts should consider whether sufficient reference data for the criteria exist when selecting these criteria in actual forensic examination. Forensic experts should also be cautious as deviation among the ages are common and well appreciated in medical practice because the biological age does not always correspond to the chronological age [43,44]. Future studies with data from other populations are necessary to verify the results of this study. In addition, we expect that the regression formulae derived from the three criteria (KHL, TVS, and LVD), presented for the first time in this study, can be successfully applied in forensic age estimation practice.

Author contribution statement

Harin Cheong: Analyzed and interpreted the data; Wrote the paper.

Sang-Seob Lee: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

The authors confirm that the data supporting the findings of this study are available in the article and its supplementary material. The datasets generated and/or analyzed during the study are available from the corresponding author upon reasonable request.

Additional information

Supplementary content related to this article has been published online.

Declaration of interest's statement

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.heliyon.2023.e13680.

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