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Validation of London Atlas for forensic age estimation in Koreans by comparing with Lee's and Willems' methods

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ABSTRACT

This cross-sectional study aimed to evaluate the applicability of the London Atlas for age estimation in the Korean population by comparing with Lee's and Willems' methods. Dental ages of 475 orthopantomographs from Korean individuals aged 4–15 years (mean 10.32 ± 3.31 years) were estimated using the London Atlas, Lee's and Willems' methods. Correlation between dental and chronological age was determined using Pearson's correlation coefficient, and the statistical difference between dental and chronological age was analyzed using a paired *t*-test. The bias (mean differences), mean absolute error, and root mean square error between dental and chronological age, stratified by age groups and estimation methods, were calculated. Differences in bias and absolute error between sexes were scrutinized using an independent-samples *t*-test. Age estimates of the three tested methods were combined and compared to those of each individual method. The London Atlas and Willems methods resulted in overestimations, whereas the Lee method led to an underestimation on the entire sample. The overall accuracy was observed in the order of Lee's method, the London Atlas, and Willems' method. The London Atlas demonstrated superior consistency of estimation performance across age groups and no significant differences in estimation performance between sexes. The combination of estimates from the London Atlas and Lee's method resulted in an enhancement in bias and accuracy. We conclude that the London Atlas, due to its bias and accuracy comparable to Lee's and Willems' methods, is applicable for forensic practice in the Korean population.

1. Introduction

The chronological age (CA) of individuals serves as a fundamental criterion for various societal functions, including pension initiation, school enrollment, employment, marriage, and legal procedures like determining the age of majority or imposing sentences in criminal cases. Chronological age is primarily determined by the individual's date of birth. However, in cases where birth documentation is missing or doubtful, the estimation of the person's biological age becomes a crucial substitute for CA. Among numerous

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biological aging indicators, dental age (DA), estimated through the analysis of developmental or degenerative changes in dentition, is consistently recognized for its superior accuracy and precision [1–6].

Tooth development, primarily regulated by genetic factors, is less influenced by nutritional and environmental factors compared to skeletal development. Consequently, age estimation based on tooth development is considered fairly accurate due to the observed reduced inter-individual variation among human populations [7,8]. Teeth's inherent resistance to physical and chemical postmortem degeneration makes them the preferred method for age estimation in forensic practices, particularly in human identification [9]. Moreover, dental development serves as an exceptional indicator for assessing physical growth, providing reference points for the diagnosis and treatment in pediatric dentistry and orthodontics [10–13].

Methodologies for age estimation with dental development can be classified into three categories. The first, known as the scoring technique [14–18], estimates age by assigning scores that correspond to specific stages of tooth development, based on established developmental standards. The second, known as the atlas approach [19–22], estimates age by comparing the current state of tooth development with a standardized pictorial representation of various developmental stages. Lastly, the metric approaches estimate age by employing measurements of features such as open apices, crown heights, and root lengths in teeth [23,24]. Among the scoring criteria, Demirjian's criteria is the most commonly used worldwide [14]. A Korean population-specific age estimation method using Demirjian's criteria has been developed and reported [25]. The authors performed a validation study to test the accuracy of this developed method (LE) and Willems' method (WL) [26] using Korean population data. The authors assert that both methods demonstrate comparable accuracy and recommend their applicability for age estimation for the Korean population [25].

The London Atlas (LD), developed by AlQahtani et al., in 2010 [22], is a comprehensive atlas covering tooth development and eruption. The utilization of this atlas enables the estimation of age spanning from 30 weeks in utero to 23.5 years of age. The authors developed the LD based on the tooth radiographic development assessment in British Caucasian and Bangladeshi populations using Moorrees et al. [16] and Bengston's criteria [27]. Unlike the dental atlases of Schour and Massler [19] and Ubelaker [20], which were developed from archaeological samples, the LD was developed using a contemporary human sample. Consequently, LD is deemed more suitable for forensic contexts involving modern humans [28]. Numerous comparative studies have consistently shown the superior performance of the LD in age estimation, outperforming both Schour and Massler's and Ubelaker's atlases [28–30]. The LD compiles reference images that depict the midpoint of an age, providing an overview of the entire developmental status of dentition. During age estimation, forensic experts match the optimal reference image from the LD with the subject's orthopantomograph, assigning the corresponding age of the matched reference image as the estimated age. The LD is generally regarded as simpler, faster, and more intuitive than the scoring techniques. Various populations have validated the LD [9,28–42], however, no studies have reported the applicability of LD in the Korean population, necessitating its validation before its implementation in Korean forensic practice. This study aimed to assess the suitability of the LD for Koreans in forensic practice by analyzing its bias and accuracy. To achieve this, the LE and WL methods, known to be applicable to Koreans [25], were employed on the same sample to calculate their bias and accuracy, and the findings were subsequently compared with those of the LD.

2. Materials and methods

The sample size calculation was carried out with the aim of attaining a statistical power of 95% to detect a bias of two months for a method characterized by a standard deviation of errors of 1 year (i.e., effect size $f^2 = 0.1667$). The calculation yielded a required sample size for overall sample of 470, and therefore, we set the sample size at 475 for this study.

Our study sample consisted of 257 orthopantomographs from males and 218 orthopantomographs from females, with an average age of 10.32 ± 3.31 years. The orthopantomographs used in this study were randomly selected from the database of Seoul St. Mary's Hospital at The Catholic University of Korea between May 11th and 15th, 2023. These orthopantomographs were taken during diagnostic procedures or dental treatments and were retrospectively collected for the purpose of this study. The inclusion criteria encompassed orthopantomographs displaying complete development of all 28 teeth, excluding the third molars, from Korean children aged between 4.00 and 15.99 years. The exclusion criteria involved orthopantomographs with unclear imaging, severe dental caries, endodontically treated teeth, pathological jawbone lesions, bilateral missing teeth, and orthopantomographs associated with patients

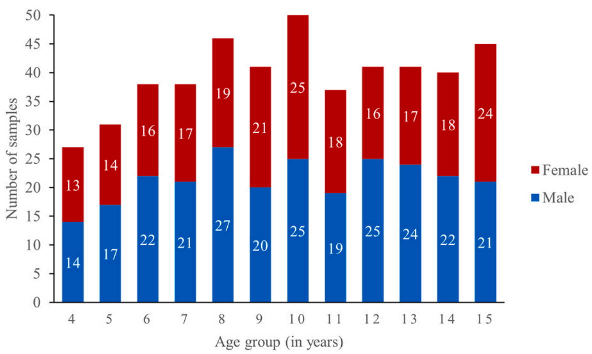

Fig. 1. Distribution of age and sex of the study samples.

having a medical history of endocrine and developmental disorders. The chronological age of the samples was determined by subtracting the date of birth from the date of the orthopantomographs and converting it to a decimal scale. We categorized the sample group into twelve age groups, as seen in Fig. 1, and stored the chronological age data in a separate spreadsheet, keeping the examiners blind to this information until the completion of age estimation.

This study was conducted in compliance with the Declaration of Helsinki and received approval from the Institutional Review Board (IRB) of Seoul St. Mary's Hospital at The Catholic University of Korea (KC23WISI0318). Given the study's retrospective nature, it was not feasible to obtain informed consent from all patients who had During age estimation, forensic experts match the optimal reference image from the LD with the subject's orthopantomograph, assigning the corresponding age of the matched reference image as the estimated age for clinical purposes. The IRB of Seoul St. Mary's Hospital at The Catholic University of Korea waived the requirement for informed consent. We anonymized all collected data, except for sex, date of birth, and the date of the During age estimation, forensic experts match the optimal reference image from the LD with the subject's orthopantomograph, assigning the corresponding age of the matched reference image as the estimated age.

The LD presents a set of schematic one-sided reference images that illustrate both deciduous and permanent dentition at various ages. The observer estimated the dental age by selecting the reference image that best aligned with the evaluated During age estimation, forensic experts match the optimal reference image from the LD with the subject's orthopantomograph, assigning the corresponding age of the matched reference image as the estimated age, considering the stage of mineralization, eruption pattern, and root resorption of all teeth observed in the left dentition, following the method suggested by AlQahtani et al. [27]. When the evaluation of the left-sided image posed challenges, we used the right-sided image for assessment [30]. In this study, we utilized only the midpoint

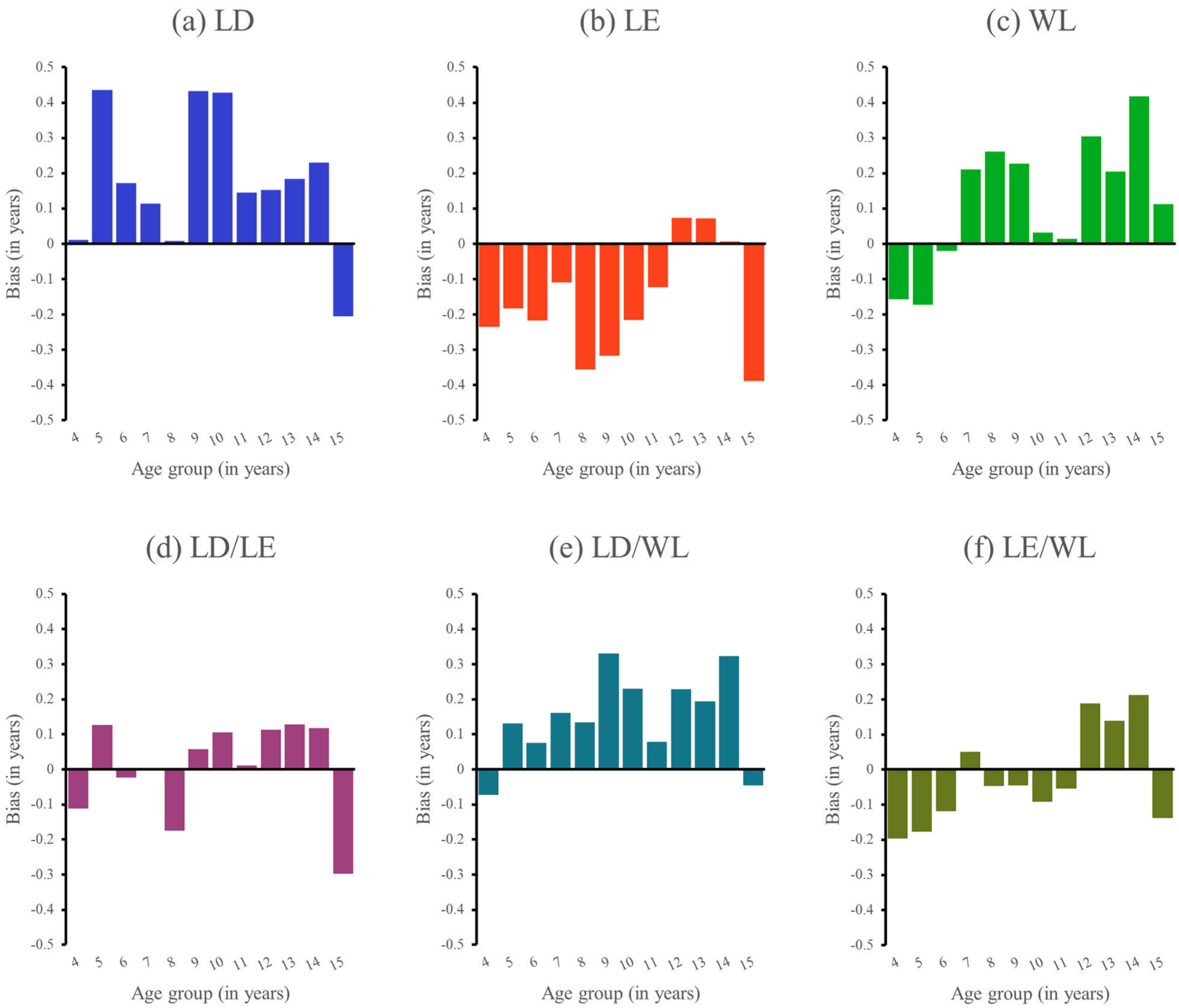

Fig. 2. The bias of age groups between dental and chronological age by estimation methods. (a) LD, London Atlas; (b) LE, Lee's method; (c) WL, Willems' method; (d) LD/LE, Method with combined estimates of LD and LE; (e) LD/WL, Method with combined estimates of LD and WL; (f) LE/WL Method with combined estimates of LE and WL.

of ages provided by LD, without employing any intermediary estimates. As the LD was unisex criteria, we applied the same criteria to both sexes when estimating age.

To estimate age using LE and WL, we assessed the maturity of seven lower left permanent teeth based on Demirjian et al.'s eight-stage criteria (A to H) [14]. In age estimation using LE, the maturity scores assigned to each stage for the seven teeth were totaled and substituted into sex-specific regression equations proposed by Lee et al. [25]. Meanwhile, in WL, the maturity score directly represents age, and the sum of the scores corresponds to the estimated age. Willems et al. presented sex-specific tables of maturity scores, showing the variation in age estimation criteria based on sex [26]. Therefore, age estimation with LE and WL is sex-dependent, unlike LD.

Two well-experienced forensic odontologists independently assessed the orthopantomographs after a pre-calibration for evaluation of dental maturity. The primary observer (SSL) re-examined a subset of fifty randomly selected orthopantomographs (about 10% of the study sample) with a minimum interval of two weeks, while the secondary observer (BYR) evaluated the same orthopantomographs. We calculated intra- and interobserver reliabilities using Cohen's kappa statistics [43], with comparisons of age estimates (for LD) or between evaluated maturation stages of seven mandibular permanent teeth (for LE and WL).

We tested data obtained from all methods for normality using the Shapiro-Wilk test and found that all data followed a normal distribution. We compared the estimated dental age with the CA for each sample, subtracting the CA from the DA. A positive value denoted an overestimation, and a negative value indicated an underestimation. We used a two-tailed paired *t*-test to assess the statistical significance of the difference between DA and CA within each method. To investigate the correlation between CA and DA in tested methods, we used Pearson's correlation coefficient (PCC). We calculated the bias (mean differences), mean absolute error (MAE), and root mean square error (RMSE) between CA and DA, for each age group and in the total sample, for each method. We also used an independent-sample *t*-test to assess the bias and absolute error between males and females across the tested methods. Following the approach outlined by Gelbrich et al. [37] for combining estimated age from multiple methods, we computed the average of the age estimates derived from LD, LE, and WL. We then calculated and compared the bias and accuracy of the combined estimates of LD and LE (LD/LE), LD and WL (LD/WL), and LE and WL (LE/WL) with those of each single method. We expressed data as means $\pm$ standard deviations, or numbers (%), based on the characteristics of the data. We considered a two-tailed P-value <0.05 as statistically significant for all tests. All statistical analyses were performed using IBM SPSS Statistics version 29.0 (IBM Co., Armonk, NY, USA).

3. Results

The mean $\pm$ standard deviation of age calculated by each method was 10.53 $\pm$ 3.36 years (LD), 10.20 $\pm$ 3.45 years (LE), and 10.48 $\pm$ 3.52 years (WL). Supplementary Table S1 contains detailed descriptive statistics for each age group and method.

We employed Kappa statistics to assess the consistency between primary and secondary observers. Both intra-observer reliability (Kappa scores of 0.866 for LD, and 0.877 for LE and WL) and interobserver reliability (scores of 0.822 for LD and 0.807 for LE and WL) displayed almost perfect agreement ($P < 0.001$) [44].

Pearson's correlation coefficients between DA and CA were significantly high, ranging from 0.986 to 0.981 for all methods ($P <$ 0.001) (Supplementary Table S2). Among the methods evaluated in the total sample, only LE showed underestimation (Bias: −0.12 years), while all other methods exhibited overestimation. LD overestimated age consistently across all age groups, except for the age group 15, while LE underestimated in all age groups, except for age groups 12, 13, and 14. WL showed underestimation only in children aged 6 and below. We have presented bias and corresponding P-values in Fig. 2 and Supplementary Table S3, segmented by age group and method.

The MAE and RMSE, assessing the accuracy of each method on the entire sample, indicated that LE was more accurate than LD and WL by approximately 0.1 years of age (Table 1). Nevertheless, any model combining estimates from LD, LE, and WL displayed higher accuracy than LE. The LD/LE model demonstrated the smallest MAE and RMSE values among all tested models (MAE: 0.42 years, RMSE: 0.56 years). LD exhibited the highest accuracy in the age group 7 (MAE: 0.30 years), with the age group 12 showing the lowest accuracy (MAE: 0.66 years), yielding a 0.33-year difference in MAE between the highest and lowest performing groups. Despite LE having a lower overall MAE of 0.08 years compared to LD, it showed a larger performance discrepancy (0.54 years in MAE) between the best and worst-performing age groups. Similarly, WL displayed a minimal disparity in overall MAE (0.01 years) compared to LD, but a significant 0.64-year difference in MAE between the best and worst-performing groups. These findings suggest an inconsistency in performance across age groups, with LE and WL demonstrating greater variation than LD (Fig. 3). In models developed with combined estimates, a diminishing trend was observed in the performance gap between the best and worst age groups (0.43 years in

Table 1
Statistical comparison between dental and chronological age by estimation methods across the entire sample using paired *t*-test.

Method	Bias (SD)	*P*	MAE (SD)	RMSE
LD	0.21 (0.66)	0.000*	0.55 (0.42)	0.69
LE	−0.12 (0.62)	0.000*	0.47 (0.43)	0.63
WL	0.16 (0.70)	0.000*	0.56 (0.45)	0.72
LD/LE	0.04 (0.56)	0.082	0.42 (0.38)	0.56
LD/WL	0.18 (0.58)	0.000*	0.47 (0.38)	0.61
LE/WL	0.02 (0.59)	0.414	0.43 (0.40)	0.59

LD, London Atlas; LE, Lee's method; WL, Willems' method; LD/LE, Method with combined estimates of LD and LE; LD/WL, Method with combined estimates of LD and WL; LE/WL Method with combined estimates of LE and WL; SD, standard deviation; MAE, mean absolute error; RMSE, root mean square error; $^*P < 0.05$ indicates a statistically significant difference.

MAE difference for LD/LE, 0.49 years for LD/WL, and 0.53 years for LE/WL). However, none of the models displayed a smaller difference than LD. The highest percentage of subjects with an MAE of less than 1 year was seen in LE/WL (93.3%), while LD had the smallest percentage (84.4%). Nevertheless, LE had the largest number of subjects with an MAE exceeding 2 years (8 cases, 1.7%), whereas LD had only one such case. Refer to Fig. 4 and Supplementary Table S4 for additional details.

Independent t-tests evaluating LD's bias and absolute error in relation to sex yielded non-statistically significant results ($P = 0.477$ for bias, 0.774 for absolute error), indicating no significant performance differences in LD's age estimation between males and females (Supplementary Table S5).

4. Discussions

This study aimed to confirm the applicability of the LD method for age estimation in Koreans. The performance of the LD was evaluated by analyzing 475 Korean orthopantomographs and calculating bias and accuracy through the comparison of DA and CA. Additionally, this study confirmed the method's suitability for the Korean population and compared it with other methods (LE, WL) commonly used in forensic practice in Korea. The results showed that the LD exhibited marginally improved accuracy (0.09 years) compared to the original LD study [28], although a statistically significant overestimation was also observed.

LD facilitates direct age estimation by comparing the overall observed dentition development in dental radiographs with sequential reference images, thus eliminating the need for scoring individual teeth. This methodology offers notable advantages, including simplicity, time-efficiency, and intuitive interpretation, surpassing the scoring technique. Furthermore, in cases involving bilateral loss

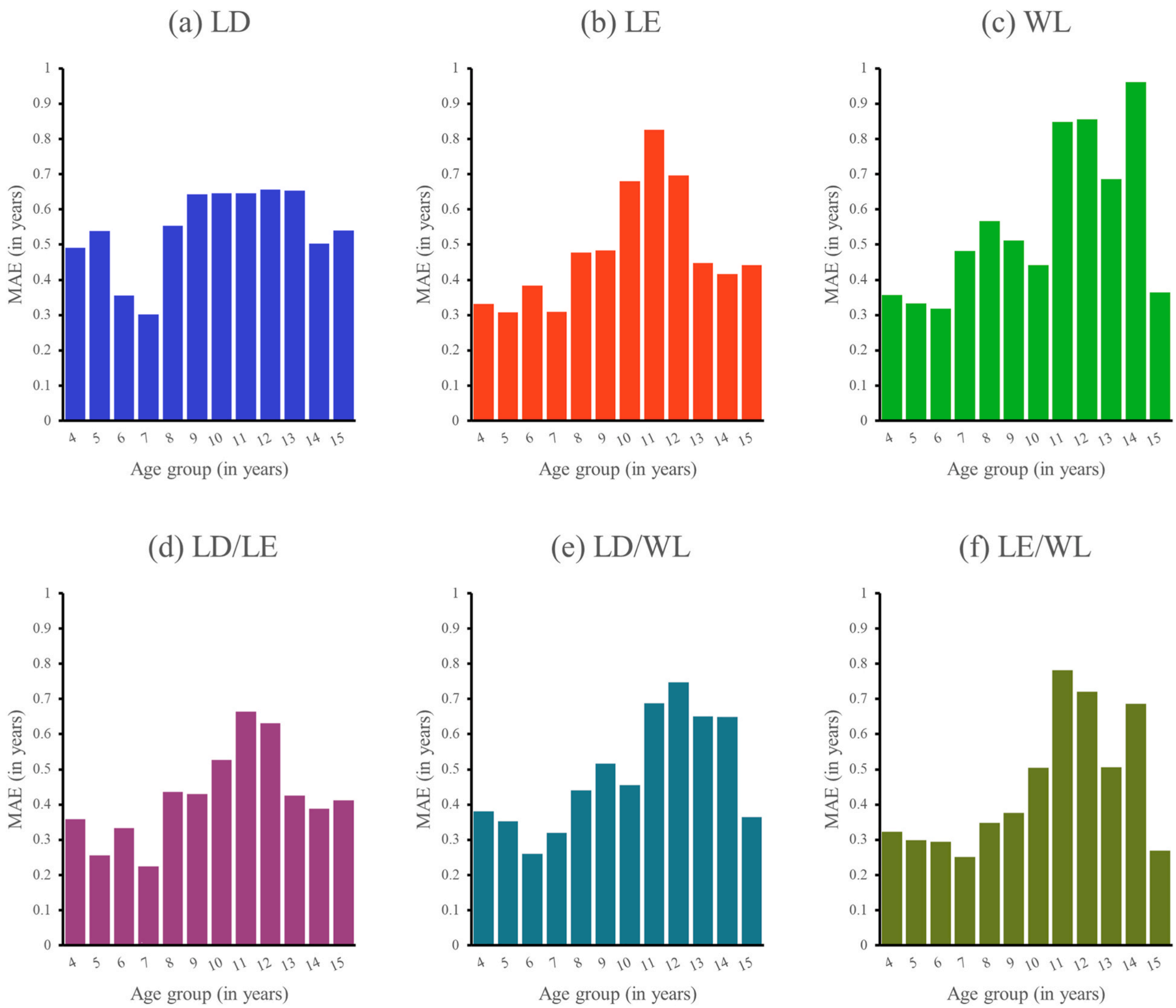

Fig. 3. The mean absolute errors of age groups between dental and chronological age by estimation methods. (a) LD, London Atlas; (b) LE, Lee's method; (c) WL, Willems' method; (d) LD/LE, Method with combined estimates of LD and LE; (e) LD/WL, Method with combined estimates of LD and WL; (f) LE/WL Method with combined estimates of LE and WL; MAE, mean absolute error.

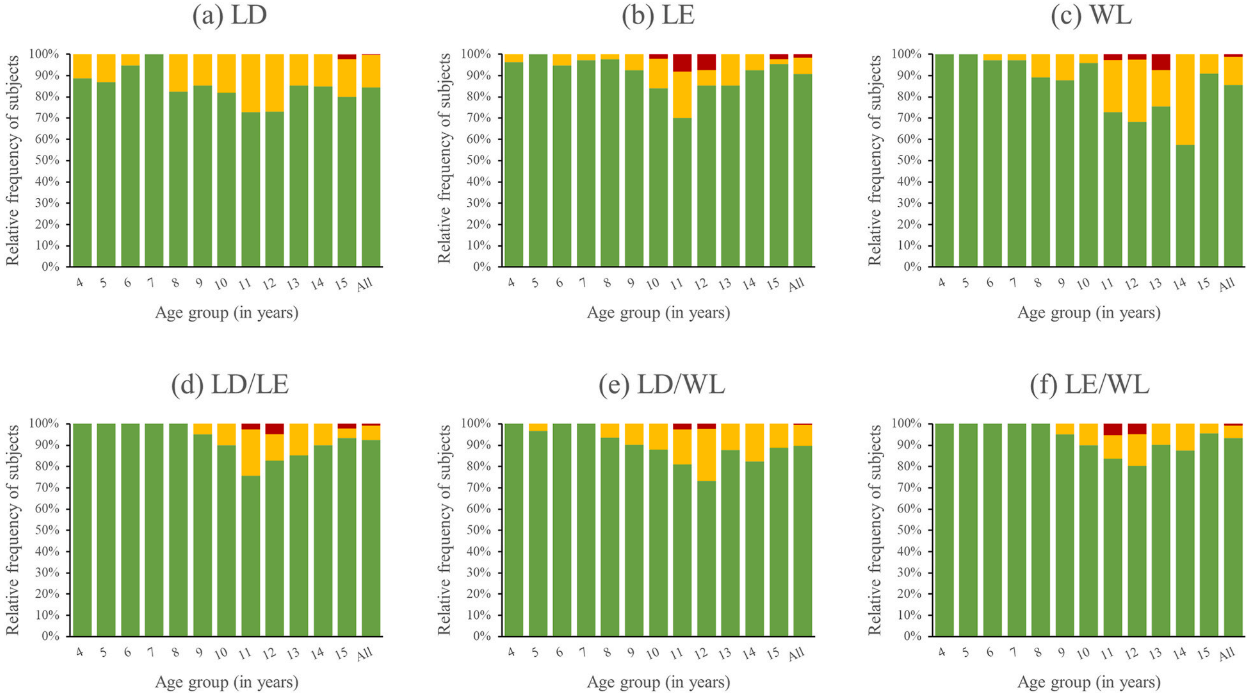

Fig. 4. Comparison of the accuracies of estimated dental age by age groups and estimation methods. (a) LD, London Atlas; (b) LE, Lee's method; (c) WL, Willems' method; (d) LD/LE, Method with combined estimates of LD and LE; (e) LD/WL, Method with combined estimates of LD and WL; (f) LE/WL Method with combined estimates of LE and WL; MAE, mean absolute error.

of specific teeth or post-mortem loss of partial dentition, it is still possible to estimate approximate age by comparing the development of the remaining teeth. These user-friendly advantages have prompted numerous validation studies conducted across diverse populations since its inception in 2010, most of which have shown satisfactory reliability and reproducibility for forensic age estimation.

This study revealed an overestimation when applying LD to the total study samples (Bias: 0.21). Similar findings have been reported in population studies conducted on Germans [37], Turks [38], Hispanics [33], Portuguese [31], Italians [10], Brazilians [45], and Indians [46]. The bias observed in these studies ranged from 0.03 [10] to 0.38 [45], consistent with our findings. Despite the statistically significant difference between DA and CA in LD, a strong positive correlation was observed between DA and CA (PCC: 0.981). Furthermore, the extent of overestimation is relatively small (approximately 2.5 months), suggesting the feasibility of applying LD in forensic practice for Koreans.

The bias of a model refers to the mean difference between DA and CA, expressed as a positive or negative value in relation to zero. By averaging the differences, positive and negative values offset each other. For instance, in this study, the observed bias of LD in the age group 4 is 0.01. This value might falsely suggest that LD is most accurate within that age group. To evaluate the accuracy of a specific model independent of bias, the absolute value of the difference between DA and CA is employed. Therefore, the accuracy of a particular model for a given group is assessed using MAE or RMSE based on absolute values. Both MAE and RMSE showed that LE exhibited smaller values than LD or WL for the entire sample, corroborating findings from previous validation studies on the Korean population. However, the discrepancy in accuracy between the most and least accurate models was only around one month. These results indicate that there is no substantial disparity in age estimation accuracy among LE, LD, or WL in forensic cases involving Koreans [4]. Therefore, LD can be effectively used in Korean forensic practice with respect to accuracy.

During the evaluation of accuracy across different age groups, LD consistently displayed the most balanced estimation performance among all the methods tested. Conversely, LE and WL showed inferior performance compared to LD in specific age groups, despite their slight superiority in overall accuracy. LE demonstrated a more noticeable increase in MAE in age groups 10, 11, and 12, whereas WL exhibited a similar trend in age groups 11, 12, and 14. In comparison, LD had a lower frequency of samples with an absolute difference between DA and CA below 1, as well as the fewest samples with a value exceeding 2. These findings imply that LD offers the most consistent accuracy across age groups for age estimation. By default, LD employs a comprehensive assessment of overall tooth development to estimate age, whereas LE or WL relies on detailed staging of the growth of the seven left permanent teeth for age estimation. The variation in accuracy across age groups can be attributed to differences in evaluation criteria and methods used. Furthermore, variations in the statistical approach employed by each method can also be regarded as a contributing factor to the divergence in accuracy across different age groups. In LE, a spline regression approach is used, where specific maturity scores are assigned as knots (90 for males, 94 for females). This involves connecting two distinct linear regressions based on those knots to estimate age. Due to the use of different regression equations associated with these maturity scores, the disparity in estimated age is expected to be greater than the variance in actual maturity scores. Consequently, there is a potential for a notable decrease in accuracy within the age group corresponding to the knots. As individuals grow older, the number of teeth that have completed their development increases, while the number of developing teeth available as variables for estimating chronological age decreases. For instance, in the age group 15, typically only the second molar is still developing, leaving only one tooth as a variable for age estimation. Consequently, samples of different ages will be extrapolated to a specific age based on the specific stage of second molar development. Hence, the accuracy of age estimation within this particular age group is expected to be lower compared to other age groups. Given the distinct sources of inaccuracy associated with specific age groups and the variations in age groups exhibiting lower estimation performance across different methods, we sought to compensate by combining the estimates from each method.

Gelbrich et al. attempted to enhance age estimation bias and accuracy by averaging the estimates from two different methods. Their findings indicated an improvement resulting from this approach [37]. Implementing this approach in our study, we observed a reduction in both the overall MAE and the frequency of samples with errors exceeding 2 years when using methods with combined estimates (LD/LE, LD/WL, and LE/WL), compared to employing a single method. These results endorse the validity of the methodological attempt by Gelbrich et al. They hypothesized that combining methods with biases in completely opposite directions would yield a more balanced average of estimates, potentially leading to more accurate age estimation [37]. In this study, we empirically proved their hypothesis by observing an enhancement in bias and accuracy when combining LD and LE, which exhibited overestimation and underestimation respectively, compared to the combination of LD and WL, both of which demonstrated overestimation.

LD was originally exclusively available as an atlas [22]. However, to enhance user convenience and accuracy, it has been commercially available as software since 2013 [28]. In recent years, numerous population studies have employed the LD software for their research [9,33–35,38,47]. While using the software, the examiner evaluates the development of individual teeth based on the Moorrees criteria [16], and the corresponding stage is inputted into the software. This input data is then compared to the software's internal database, enabling the generation of an estimated age through comparison with the database. According to Adams et al. [32], age estimation using software involves the evaluation of individual tooth development, suggesting a potential divergence in the analysis mechanism compared to original LD, which comprehensively considers the development of the entire dentition. In the original LD, certain stages are depicted with indistinguishable similarity. Notably, the figures representing age groups 12.5 to 15.5 exhibit a considerable resemblance, potentially leading to an increased error in age estimation within this specific age group. The use of the software is anticipated to alleviate errors stemming from the aforementioned limitations of the original LD. However, it should be noted that the software was unavailable during the period of this study (May to June 2023) due to a technical error, therefore, it could not be applied for this study. A future comparative study to evaluate the estimation performance of the LD software for the Korean population and compare it with that of the original LD should be performed.

This is the first study to validate the applicability of LD in the Korean population. However, there are significant limitations of this research in sample collection. First limitation of this study is the imbalance in the sample size across different age ranges and sexes. While ideally, the samples should have been stratified to reflect proportional representation for each age group, the use of random sampling led to variations in the sample size distribution between sexes and among different age groups. Second limitation is its reliance on data solely from a single institution. These limitations may have an impact on the generalization of the results to entire Korean population and should be considered when interpreting the findings of this study. Furthermore, the study design did not provide full control over nutritional, environmental, and sociocultural factors that can potentially influence dental development. These factors also should be considered when interpreting the results of this study.

5. Conclusions

In this study, the bias and accuracy of LD, LE, and WL were examined, revealing that LD demonstrated bias and accuracy comparable to those of LE and WL in age estimation for the Korean population. These findings provide scientific validation for the potential application of LD in age estimation for Koreans. Furthermore, it was noticed that the combination of LD and LE estimates might offer a potential refinement in the accuracy of age estimation. Future research should involve large-scale population studies using multi-institutional data to verify our findings and compare them with the results from the LD software, which was not assessed in this study. Such follow-up studies could contribute to identifying a more effective age estimation method for use in Korean practice.

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Author contribution statement

Harin Cheong: Contributed reagents, materials, analysis tools or data; Wrote the paper. Byung-Yoon Roh: Performed the experiments. Akiko Kumagai: Analyzed and interpreted the data. Sehyun Oh: Contributed reagents, materials, analysis tools or data. Sang-Seob Lee: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Data availability statement

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

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Sang-Seob Lee reports financial support was provided by National Research Foundation of Korea.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e19957.

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