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Evaluation of the accuracy of Nolla, Cameriere-European, and Blenkin-Evans methods for dental age estimation of Turkish children

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Abstract

Dental age (DA) estimation plays a crucial role in forensic investigations, clinical diagnosis, and treatment planning. It is considered more reliable than skeletal methods due to the predictable nature of dental development. This study aimed to evaluate the accuracy of three DA estimation methods—Nolla method, Cameriere-European formula, and Blenkin-Evans method—in Turkish children aged 6–14 years. A total of 1014 panoramic radiographs were analyzed. DA was estimated using the three methods and compared with chronological age (CA). Accuracy was assessed based on mean absolute error (MAE), mean difference (DA–CA), and correlation coefficients. Statistical analyses were performed to determine significant differences among methods. The Cameriere-European formula demonstrated the lowest MAE (0.44 for boys, 0.48 for girls, and 0.46 for all samples), indicating the highest accuracy, followed by the Blenkin-Evans (0.54 for boys, 0.53 for girls, and 0.54 for all samples) and Nolla (0.57 for boys, 0.65 for girls, and 0.61 for all samples) methods. However, the Cameriere-European formula slightly underestimated CA, particularly in older children. The Blenkin-Evans method showed relatively stable accuracy but overestimated CA in both sexes. The Nolla method generally underestimated CA, except in boys, where it slightly overestimated age. All three methods exhibited strong correlations with CA (Spearman *rho* correlation coefficients ranging from 0.953 to 0.970, all $p < .001$). The Cameriere-European formula provided the most accurate DA estimation method, followed by the Blenkin-Evans and Nolla methods for Turkish children from the Northwestern Anatolia. However, the observed biases highlight the need for population-specific calibrations.

Keywords

Dental age estimation, Nolla method, Cameriere-European formula, Blenkin-Evans method, forensic dentistry, forensic odontology

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Introduction

Dental development serves as a critical parameter for age estimation in disciplines such as pediatric dentistry, orthodontics, and forensic science. In particular, it offers a dependable metric for identifying unknown children and adolescents, as dental maturation is generally less affected by environmental influences than skeletal development.[1] However, due to variations in growth patterns across populations, notable differences can occur between chronological age (CA) and biological indicators such as dental age (DA). These discrepancies highlight the limitation of using universal age estimation models and underscore the need for population-specific validation. Recent literature has increasingly stressed the importance of calibrating age estimation techniques according to specific population data. In ethnically diverse countries, it is further advised to assess the performance of established methods regionally to ensure their accuracy.[2] Consequently, a range of techniques have been proposed in the literature to estimate DA effectively. The Nolla method[3] is one of the earliest techniques, classifying the mineralization of permanent teeth into 10 stages from 0 to 10. Nolla categorically defined the developmental stages of each tooth and correlated these stages with specific age estimates. The Demirjian method,[4] originally formulated and extensively applied within the French-Canadian population, estimates DA by

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evaluating seven permanent mandibular teeth based on eight defined calcification stages, labeled from A to H. Despite its widespread use, subsequent studies have reported that this method frequently overestimates CA when applied to other populations.[5,6] Consequently, several modifications of the method have been developed.

Another approach, the Blenkin-Evans method,[7] is a modification of the Demirjian method adapted for the Australian pediatric population. Blenkin and Evans reanalyzed Demirjian's original data for Australian children and developed new sex-specific age tables and regression coefficients.[7] To address the systematic bias associated with the Demirjian method, modifications have been proposed to enhance its accuracy. Among these, the Blenkin-Evans method has gained attention and has yielded promising outcomes, especially in studies involving Turkish pediatric populations.[2,8]

In recent years, radiographic measurement-based techniques, such as the Cameriere method, have gained prominence. Cameriere et al.[9] introduced a regression-based formula that estimates DA by quantitatively measuring the width of apical openings in seven permanent mandibular teeth (on the left side) using panoramic radiographs. In 2007, a study involving 2652 European children led to the adaptation of this equation for the European population, resulting in the "Cameriere-European formula."[10] This formula estimates a child's age using variables such as the number of open apices and the total amount of apical openings. The method is considered highly accurate, with an average estimation error of less than one year. Studies conducted in different countries have demonstrated that the Cameriere-European formula can estimate CA in children aged 6–14 years with a typical deviation of $\leq$1 year.[11]

To date, no comprehensive study in Türkiye has simultaneously evaluated the traditional morphological Nolla method alongside the modern Cameriere-European formula and Blenkin-Evans methods. Accordingly, the present study aims to compare the accuracy of the Nolla method, Cameriere-European formula, and Blenkin-Evans method in estimating DA in healthy Turkish children aged 6 to 14 years residing in Northwestern Anatolia. The research also seeks to identify the most reliable method for this population. The null hypothesis states that there is no statistically significant difference among the three methods in terms of estimation accuracy.

Methods

Study design, ethical approval, inclusion and exclusion criteria

This investigation was designed as a cross-sectional and retrospective study. Digital panoramic radiographs of children aged 6–14 years, residing in the Northwestern Anatolia region and attending the Pediatric Dentistry Clinic at Çanakkale Onsekiz Mart University between January and December 2022, were evaluated. Radiographic imaging was performed using a Planmeca Promax 2D device (Planmeca Oy, Helsinki, Finland) with exposure parameters set at 60–64 kV, 5 mA, and 14 s.

The study was carried out in alignment with the ethical principles set forth in the Declaration of Helsinki concerning research involving human subjects. Ethical approval was granted by the Clinical Research Ethics Committee of Çanakkale Onsekiz Mart University (Protocol No: 2021/04-11). Prior to participation, written informed consent was obtained from the parents or legal guardians of all children.

Inclusion criteria consisted of children who underwent panoramic radiography between January and December 2022, were aged between 6 and 14 at the time of imaging, had diagnostically excellent radiographs (Grade 1), according to the United Kingdom National Radiological Protection Board,[12] and were free from any systemic disorders or syndromes. Eligible participants were also required to exhibit a complete set of permanent teeth (excluding third molars) in both jaws, with all teeth appearing healthy and clearly visible. Children were excluded if they presented with hyperdontia, hypodontia, or any dental anomalies; periapical or periodontal pathology; prior tooth loss; a history of orthodontic treatment; or evidence of jawbone cysts, tumors, or previous orofacial trauma.

Sample size calculation

The minimum required sample size for the study was calculated using G*Power software version 3.1.9.7 (Universität Kiel, Kiel, Germany). The calculation was based on data from a previous study,[2] which evaluated the accuracy of the traditional Cameriere and Cameriere-European formulas, and Willems and Blenkin-Evans methods in a pediatric population from Central Anatolia. In that study, for girls aged between 7 and 7.99 years, the mean DA was reported as 7.98 ± 0.77 using the Cameriere-European formula and 7.71 ± 0.84 using the Blenkin-Evans method, with the difference being statistically significant ($p < .001$). Using these parameters, the effect size was determined to be 0.3350872. Based on this effect size, with a significance level (α) of 0.05 and a statistical power of 99%, the minimum sample size required for the study was calculated to be 564 participants.

Chronological age calculation

Each child's CA was calculated in decimal years by determining the difference between the date of panoramic radiograph acquisition and the date of birth. The fractional parts of the years were expressed as decimal age to allow for a more precise assessment. The age distribution of the

Table 1. Comparison of DA and CA for three methods in both sexes and the total sample.

	CA Mean ± SD	Method	DA Mean ± SD	DA-CA Mean ± SD	MAE	Std. Error Mean	95% CI Lower	95% CI Upper	*t*	*p*
Boys	10.31 ± 2.4	NM	10.62 ± 2.36	0.31 ± 0.72	0.57 ± 0.44	0.03	0.25	0.37	9.825	**<.001**[b]
		CEF	10.15 ± 1.92	−0.16 ± 0.9	0.44 ± 0.34	0.04	−0.24	−0.08	−4.140	**<.001**[b]
		BEM	10.45 ± 2.42	0.14 ± 0.69	0.54 ± 0.4	0.03	0.08	0.20	4.802	**<.001**[a]
Girls	9.95 ± 2.46	NM	9.7 ± 2.42	−0.25 ± 0.75	0.65 ± 0.46	0.03	−0.32	−0.18	−7.296	**<.001**[b]
		CEF	9.89 ± 2.08	−0.06 ± 0.79	0.48 ± 0.36	0.04	−0.13	0.01	−1.634	.103[a]
		BEM	10.07 ± 2.56	0.12 ± 0.64	0.53 ± 0.39	0.03	0.06	0.17	4.069	**<.001**[a]
Total	10.14 ± 2.43	NM	10.18 ± 2.43	0.04 ± 0.78	0.61 ± 0.45	0.02	−0.01	0.09	1.658	.098[a]
		CEF	10.02 ± 2	−0.11 ± 0.85	0.46 ± 0.35	0.03	−0.16	−0.06	−4.209	**<.001**[b]
		BEM	10.27 ± 2.49	0.13 ± 0.66	0.54 ± 0.4	0.02	0.09	0.17	6.294	**<.001**[a]

CA: chronological age; DA: dental age; SD: standard deviation; NM: Nolla method; CEF: Cameriere-European formula; BEM: Blenkin-Evans method; MAE: mean absolute error; CI: confidence interval; Std: standard.
Note: Bold values mean statistically significant.
[a]Paired *t*-test.
[b]Wilcoxon signed-rank test.

sample was categorized into nine groups, ranging from 6.0 to 14.9 years, with each group representing whole-year intervals from 6 to 14 years (Table 1).

Dental age estimation

- *Nolla method*

The seven permanent teeth in the left mandibular quadrant (teeth numbers #31–#37) were evaluated according to the ten calcification stages defined by Nolla, ranging from 0 (absence of a germ) to 10 (complete apical closure). The most appropriate developmental stage was assigned to each tooth; if a tooth's development was between two stages, the corresponding intermediate values (0.2, 0.5, or 0.7) suggested by Nolla were used. The age values corresponding to the stage of each tooth were summed, and this total was compared with the sex-specific reference values in Nolla's reference table to determine the individual's DA.[3]

- *Cameriere-European formula*

On panoramic radiographs, the apical widths of the seven permanent teeth in the left mandibular arch were measured digitally in millimeters. ImageJ software (version 1.49v; U.S. National Institutes of Health, Bethesda, MD, USA) was utilized for computer-aided measurements. Teeth with fully formed roots (closed apices) were recorded as N0. In teeth with open apices, the distance between the inner borders of the apical opening was measured (Ai, $i = 1$ to 5 for single-rooted teeth). For the first and second molars, both root apex widths were measured and summed (Ai, $i = 6,7$). To minimize errors due to differences in radiographic magnification or angulation, each measurement was standardized by dividing by the corresponding tooth length (Li, $i = 1$ to 7). $x5$ represents the ratio of the apical width of the second premolar to its overall length. The sum of all Ai/Li ratios was denoted as (s). These values were incorporated into the Cameriere regression model, which was developed for European pediatric populations, to calculate the DA of each subject.[10] The regression equation used was as follows: $\text{Age} = 8.387 + 0.282\ \text{g} - 1.692 \cdot x5 + 0.835 \cdot \text{N0} - 0.116\ \text{s} - 0.139\ \text{s} \cdot \text{N0}$, where g is a sex variable (1 for males, 0 for females), s is the total of the Ai/Li ratios, and N0 is the number of teeth with closed apices.

- *Blenkin-Evans method*

The seven left mandibular permanent teeth were assessed using Demirjian's developmental staging system, which classifies tooth formation into eight stages (A–H). Each developmental stage was then converted into an age estimate using the sex-specific conversion tables provided by Blenkin and Evans, developed for the Australian population.[7] The mean of the age estimates for the seven teeth was calculated to determine the individual's DA based on the Blenkin-Evans method.

Measurement repeatability

Radiographic evaluations were conducted by two experienced pediatric dentists who were blinded to the CAs of the children. Each radiograph was independently assessed twice by the observers, with randomized coding. To ensure consistency in the evaluation process, a calibration procedure was conducted prior to data collection. Two hundred radiographs were re-examined with a one-month interval to evaluate intra-observer consistency. Inter- and intra-observer reliability was assessed through comparisons of repeated measurements using the Intraclass Correlation

Coefficient (ICC). The final DA for each case was determined as the average of the two observers' measurements.

Statistical analysis

All statistical analyses were carried out using SPSS software version 25.0 (IBM Corp., Chicago, IL, USA). The difference between DA and CA (DA–CA) was computed in years for each individual. The normality of the data was tested using the Kolmogorov–Smirnov test. For normally distributed datasets, paired *t*-tests were used to determine the significance of DA–CA differences, while the Wilcoxon signed-rank test was applied for non-normally distributed data. Statistical significance was set at $p < .05$. The mean difference between DA and CA was analyzed across age groups and sexes, and deviations from zero were evaluated using the relevant paired tests. In addition, the mean absolute error (MAE) was calculated for each method to assess estimation accuracy. The association between DA and CA was examined using Spearman's rank correlation coefficient. Accuracy within ±1 year was evaluated by determining the absolute difference |DA–CA| and calculating its percentage in relation to CA for each case.

Results

The inter-observer agreement for assessing dental development stages was high, with an ICC value of 0.84. Intra-observer agreement was also strong, with values of 0.89 for the first observer and 0.87 for the second. The mean age of the children included in the study was 10.1 years, with 52.1% being boys and 47.9% being girls. When the distribution of the sample group by age and sex was examined, a total of 113 panoramic radiographs were evaluated in the 6–6.99 age group (46 boys and 67 girls), 138 in the 7–7.99 age group (70 boys and 68 girls), 126 in the 8–8.99 age group (66 boys and 60 girls), 97 in the 9–9.99 age group (51 boys and 46 girls), 140 in the 10–10.99 age group (71 boys and 69 girls), 123 in the 11–11.99 age group (67 boys and 56 girls), 102 in the 12–12.99 age group (62 boys and 40 girls), 139 in the 13–13.99 age group (75 boys and 64 girls), and 36 in the 14–14.99 age group (20 boys and 16 girls). In total, panoramic radiographs of 1014 children, including 528 boys and 486 girls, were evaluated in the study.

Table 1 shows the differences between estimated DA and CA across sexes and for the total sample. In the overall sample, the Cameriere-European formula underestimated DA by 0.11 years, while the Blenkin-Evans method overestimated it by 0.13 years, both statistically significant ($p < .001$). Among boys, the Nolla method overestimated DA by 0.31 years, the Cameriere-European formula underestimated it by 0.16 years, and the Blenkin-Evans method overestimated it by 0.14 years (all $p < .001$). Among girls, the Nolla method underestimated DA by 0.25 years, while the Blenkin-Evans method overestimated it by 0.12 years (both $p < .001$). No statistically significant difference was found in girls using the Cameriere-European formula ($p = .103$) or in the total sample using the Nolla method ($p = .098$). Both in boys and girls, the Cameriere-European formula tended to underestimate CA, while the Blenkin-Evans method tended to overestimate it. The MAE values were below 1 year for all groups, ranked from lowest to highest as follows: Cameriere-European formula < Blenkin-Evans method < Nolla method.

Table 2 presents the comparison of DA and CA across different age groups in boys. The Nolla method overestimated CA in all age groups ($p < .05$) except for the 13-year-old group (-0.06 ± 1.03) ($p = .638$). The Cameriere-European formula overestimated CA in boys aged 6, 7, and 9 years (all $p < 0.001$) but significantly underestimated it in those aged 11, 12, 13, and 14 years (all $p < .001$). The Blenkin-Evans method overestimated CA in boys aged 8 ($p = .004$), 9 ($p = .001$), 10 ($p < .001$), 11 ($p < .001$), and 12 ($p = .047$) years, while underestimated aged 13 ($p = .002$) and 14 ($p = .009$), with statistically significant levels. Figure 1 illustrates the differences between DA and CA across different age groups using the three methods in boys.

The comparison between DA and CA across different age groups in girls is presented in Table 3. The Nolla method significantly underestimated CA in all age groups ($p < .05$) except for the 6, 8, 9, and 14 years (all $p > .05$). The Cameriere-European formula overestimated CA in girls aged 6, 8, and 9 years ($p < .001$, $p = .036$, and $p = .001$, respectively), while significantly underestimating it in those aged 10 ($p < .001$), 11 ($p < .001$), 12 ($p = .001$), 13 ($p < .001$), and 14 years ($p < 0.001$). The Blenkin-Evans method significantly underestimated CA in girls aged 7 and 14 years ($p = .025$ and $p = .002$, respectively), while overestimating it in those aged 8 ($p = .012$), 9 ($p = .001$), 10 ($p = .001$), 11 ($p < .001$), and 12 ($p = .016$) years. Figure 2 illustrates the differences between DA and CA across different age groups in girls using the three methods.

The correlation between DA and CA was strong for all three methods in both sexes, with Spearman's correlation coefficients ranging from 0.953 to 0.970 (all $p < .001$) (Table 4). When assessing accuracy within ±1 year, the Nolla method showed an accuracy rate of 80.9% in boys, followed by 76% for the Cameriere-European formula and 85.3% for the Blenkin-Evans method. In girls, the accuracy rates were 84.4% for the Nolla method, 80% for the Cameriere-European formula, and 85.8% for the Blenkin-Evans method. Overall, the highest accuracy was observed with the Blenkin-Evans method at 85.5%, followed by the Nolla method at 82.5%, and the Cameriere-European formula at 77.9%.

Table 2. Comparison of DA and CA according to three methods among boys.

Age-group	CA Mean ± SD	Method	DA Mean ± SD	DA-CA Mean ± SD	MAE	Std. Error Mean	95% CI Lower	95% CI Upper	*t*	*p*
6	6.49 ± 0.28	NM	6.99 ± 0.64	0.5 ± 0.5	0.55 ± 0.33	0.07	0.35	0.65	6.836	**<.001**[a]
		CEF	7.55 ± 0.19	1.06 ± 0.27	0.16 ± 0.11	0.04	0.98	1.13	26.782	**<.001**[a]
		BEM	6.55 ± 0.62	0.06 ± 0.48	0.52 ± 0.32	0.07	−0.08	0.20	0.880	.384[b]
7	7.36 ± 0.25	NM	7.83 ± 0.44	0.47 ± 0.41	0.34 ± 0.27	0.05	0.37	0.57	9.547	**<.001**[a]
		CEF	7.7 ± 0.16	0.35 ± 0.26	0.12 ± 0.1	0.03	0.29	0.41	11.041	**<.001**[b]
		BEM	7.4 ± 0.47	0.05 ± 0.43	0.36 ± 0.29	0.05	−0.06	0.15	0.922	.360[b]
8	8.47 ± 0.3	NM	8.96 ± 0.66	0.49 ± 0.6	0.49 ± 0.44	0.07	0.34	0.64	6.597	**<.001**[a]
		CEF	8.53 ± 0.68	0.06 ± 0.58	0.54 ± 0.41	0.07	−0.09	0.20	0.789	.433[a]
		BEM	8.73 ± 0.77	0.26 ± 0.69	0.58 ± 0.5	0.09	0.09	0.43	3.010	**.004**[b]
9	9.53 ± 0.29	NM	9.9 ± 0.67	0.37 ± 0.66	0.57 ± 0.35	0.09	0.18	0.55	3.982	**<.001**[a]
		CEF	9.98 ± 0.56	0.46 ± 0.54	0.48 ± 0.29	0.08	0.31	0.61	6.071	**<.001**[b]
		BEM	9.91 ± 0.8	0.39 ± 0.78	0.69 ± 0.39	0.11	0.17	0.61	3.516	**.001**[b]
10	10.5 ± 0.29	NM	10.77 ± 0.65	0.27 ± 0.57	0.51 ± 0.4	0.07	0.14	0.41	4.027	**<.001**[b]
		CEF	10.44 ± 0.29	−0.06 ± 0.33	0.19 ± 0.21	0.04	−0.13	0.02	−1.467	.147[a]
		BEM	10.85 ± 0.72	0.35 ± 0.64	0.57 ± 0.43	0.08	0.20	0.50	4.624	**<.001**[a]
11	11.43 ± 0.28	NM	11.7 ± 0.83	0.27 ± 0.76	0.67 ± 0.48	0.09	0.09	0.46	2.952	**.004**[b]
		CEF	10.91 ± 0.57	−0.51 ± 0.53	0.38 ± 0.42	0.06	−0.64	−0.38	−7.876	**<.001**[b]
		BEM	11.78 ± 0.78	0.36 ± 0.71	0.62 ± 0.46	0.09	0.18	0.53	4.100	**<.001**[a]
12	12.53 ± 0.3	NM	12.76 ± 0.83	0.24 ± 0.79	0.64 ± 0.51	0.10	0.04	0.44	2.359	**.022**[b]
		CEF	11.65 ± 0.84	−0.88 ± 0.82	0.7 ± 0.46	0.10	−1.09	−0.67	−8.424	**<.001**[a]
		BEM	12.7 ± 0.71	0.17 ± 0.68	0.57 ± 0.42	0.09	0.00	0.35	2.027	**.047**[a]
13	13.49 ± 0.27	NM	13.43 ± 1.06	−0.06 ± 1.03	0.87 ± 0.6	0.12	−0.29	0.18	−0.472	.638[b]
		CEF	12.43 ± 1.13	−1.06 ± 1.09	0.98 ± 0.56	0.13	−1.31	−0.81	−8.396	**<.001**[a]
		BEM	13.2 ± 0.79	−0.28 ± 0.77	0.65 ± 0.45	0.09	−0.46	−0.11	−3.178	**.002**[a]
14	14.24 ± 0.18	NM	14.6 ± 0.81	0.36 ± 0.75	0.52 ± 0.61	0.17	0.00	0.71	2.113	**.048**[a]
		CEF	13.59 ± 0.67	−0.65 ± 0.64	0.43 ± 0.51	0.14	−0.95	−0.36	−4.602	**<.001**[b]
		BEM	13.99 ± 0.43	−0.26 ± 0.39	0.3 ± 0.3	0.09	−0.44	−0.07	−2.911	**.009**[b]

CA: chronological age; DA: dental age; SD: standard deviation; NM: Nolla method; CEF: Cameriere-European formula; BEM: Blenkin-Evans method; MAE: mean absolute error; CI: confidence interval; Std: standard.
Note: Bold values mean statistically significant.
[a]Paired *t*-test.
[b]Wilcoxon signed-rank test.

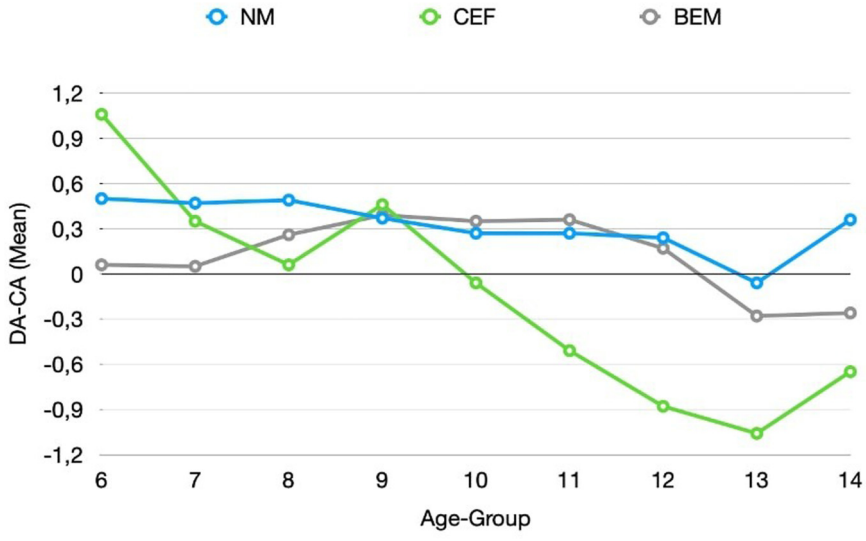


Figure 1. Comparison of DA and CA among three different methods in boys.
NM: Nolla method; CEF: Cameriere-European formula; BEM: Blenkin-Evans method; DA: dental age; CA: chronological age.

Table 3. Comparison of DA and CA according to three methods among girls.

Age-Group	CA Mean ± SD	Method	DA Mean ± SD	DA-CA Mean ± SD	MAE	Std. Error Mean	95% CI Lower	95% CI Upper	*t*	*p*
6	6.43 ± 0.32	NM	6.39 ± 0.58	−0.05 ± 0.4	0.47 ± 0.34	0.05	−0.14	0.05	−0.926	.358[b]
		CEF	7.37 ± 0.14	0.94 ± 0.3	0.11 ± 0.09	0.04	0.86	1.01	25.585	**<.001**[a]
		BEM	6.37 ± 0.61	−0.06 ± 0.42	0.49 ± 0.36	0.05	−0.16	0.04	−1.150	.254[a]
7	7.47 ± 0.28	NM	7.3 ± 0.46	−0.17 ± 0.42	0.36 ± 0.29	0.05	−0.27	−0.07	−3.346	**.001**[a]
		CEF	7.52 ± 0.22	0.04 ± 0.29	0.17 ± 0.15	0.04	−0.03	0.11	1.219	.227[b]
		BEM	7.35 ± 0.51	−0.13 ± 0.45	0.41 ± 0.31	0.05	−0.24	−0.02	−2.297	**.025**[a]
8	8.43 ± 0.26	NM	8.42 ± 0.7	−0.01 ± 0.6	0.57 ± 0.39	0.08	−0.17	0.14	−0.188	.852[b]
		CEF	8.6 ± 0.73	0.17 ± 0.61	0.57 ± 0.44	0.08	0.01	0.33	2.141	**.036**[a]
		BEM	8.66 ± 0.79	0.23 ± 0.68	0.62 ± 0.49	0.09	0.05	0.40	2.600	**.012**[b]
9	9.53 ± 0.31	NM	9.4 ± 0.56	−0.13 ± 0.55	0.44 ± 0.34	0.08	−0.29	0.03	−1.613	.114[b]
		CEF	9.85 ± 0.55	0.32 ± 0.6	0.44 ± 0.33	0.09	0.15	0.50	3.659	**.001**[a]
		BEM	9.94 ± 0.79	0.41 ± 0.76	0.66 ± 0.42	0.11	0.19	0.63	3.674	**.001**[a]
10	10.46 ± 0.27	NM	10.01 ± 0.54	−0.45 ± 0.56	0.45 ± 0.31	0.07	−0.58	−0.31	−6.556	**<.001**[b]
		CEF	10.23 ± 0.43	−0.22 ± 0.49	0.2 ± 0.38	0.06	−0.34	−0.11	−3.815	**<.001**[a]
		BEM	10.7 ± 0.59	0.25 ± 0.6	0.45 ± 0.37	0.07	0.10	0.39	3.419	**.001**[b]
11	11.46 ± 0.27	NM	11.19 ± 0.74	−0.27 ± 0.7	0.61 ± 0.41	0.09	−0.46	−0.08	−2.868	**.006**[a]
		CEF	10.96 ± 0.61	−0.5 ± 0.59	0.52 ± 0.31	0.08	−0.66	−0.35	−6.409	**<.001**[b]
		BEM	11.86 ± 0.72	0.4 ± 0.69	0.6 ± 0.39	0.09	0.22	0.58	4.382	**<.001**[a]
12	12.43 ± 0.31	NM	12.07 ± 0.9	−0.36 ± 0.77	0.73 ± 0.51	0.12	−0.60	−0.11	−2.963	**.005**[a]
		CEF	11.89 ± 1.09	−0.54 ± 0.95	0.94 ± 0.52	0.15	−0.84	−0.24	−3.593	**.001**[a]
		BEM	12.71 ± 0.82	0.28 ± 0.7	0.68 ± 0.45	0.11	0.05	0.50	2.508	**.016**[b]
13	13.52 ± 0.28	NM	13 ± 1.24	−0.51 ± 1.23	0.88 ± 0.86	0.15	−0.82	−0.21	−3.336	**.001**[b]
		CEF	12.89 ± 0.91	−0.62 ± 0.83	0.75 ± 0.51	0.10	−0.83	−0.41	−5.976	**<.001**[a]
		BEM	13.43 ± 0.6	−0.09 ± 0.56	0.49 ± 0.35	0.07	−0.23	0.05	−1.292	.201[b]
14	14.2 ± 0.19	NM	13.8 ± 1.53	−0.4 ± 1.51	1.31 ± 0.7	0.38	−1.20	0.41	−1.051	.310[a]
		CEF	13.31 ± 0.82	−0.89 ± 0.79	0.63 ± 0.5	0.20	−1.31	−0.47	−4.504	**<.001**[b]
		BEM	13.72 ± 0.53	−0.48 ± 0.52	0.4 ± 0.33	0.13	−0.76	−0.21	−3.712	**.002**[a]

CA: chronological age; DA: dental age; SD: standard deviation; NM: Nolla method; CEF: Cameriere-European formula; BEM: Blenkin-Evans method; MAE: mean absolute error; CI: confidence interval; Std: standard.

Note: Bold values mean statistically significant.

[a]Paired *t*-test.

[b]Wilcoxon signed-rank test.

Discussion

Accurate age estimation plays a pivotal role in clinical diagnosis, orthodontic and pediatric dental treatment planning, as well as in forensic applications.[13] While both skeletal and dental indicators are utilized for determining age, dental development is often regarded as a more consistent marker due to its relative stability against environmental and hormonal influences.[14] Among age estimation methods, radiographic techniques are widely preferred because they are non-invasive, easy to apply, and highly reproducible.[15] Nevertheless, it is essential to validate age estimation methods for each population, as their performance may vary depending on ethnic and regional factors.[16] The present study aimed to assess the accuracy of three widely referenced DA estimation methods—the Nolla method, the Cameriere-European formula, and the Blenkin-Evans method—in a cohort of Turkish children from Northwestern Anatolia. The results demonstrated statistically significant discrepancies among the three methods, thereby leading to the rejection of the null hypothesis that they yield comparable outcomes.

For DA estimation, the calculated DA may be either higher or lower than an individual's CA. The primary criterion for assessing a method's performance is that the MAE should be as small as possible, ideally approaching zero. The mean difference between DA and CA reflects the systematic bias of a method, whereas the MAE value represents the overall accuracy, independent of bias.[17,18] In this study, the Cameriere-European formula exhibited the lowest MAE among the three methods, followed by the Blenkin-Evans and Nolla methods. When analyzed by age groups, the Cameriere-European formula demonstrated very high accuracy (MAE ≤ 0.2) for both sexes in the 6-, 7-, and 10-year-old groups. For the Nolla method, the MAE

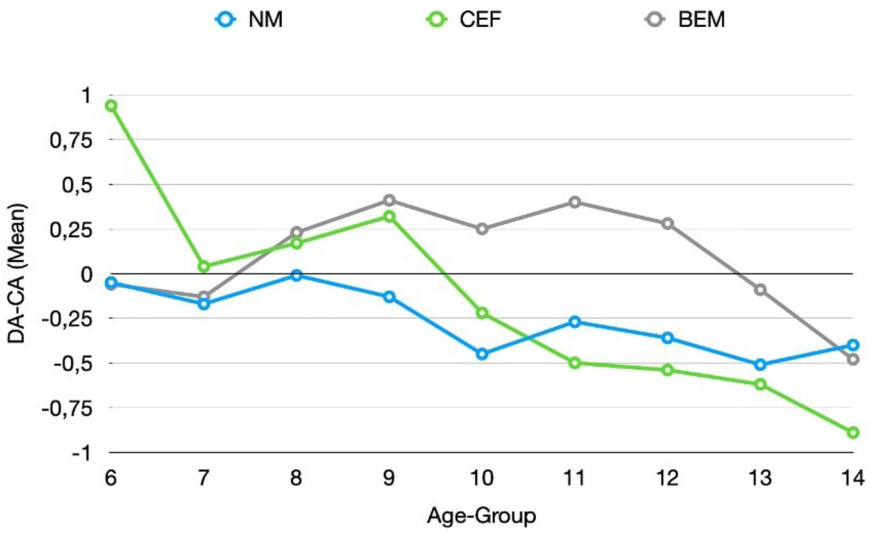


Figure 2. Comparison of DA and CA among three different methods in girls.
NM: Nolla method; CEF: Cameriere-European formula; BEM: Blenkin-Evans method; DA: dental age; CA: chronological age.

Table 4. Correlation between DA and CA according to Spearman's rank correlation coefficient (*r* value) for three methods in both sexes and the total sample.

Method	*r*-/ *p*-values	Boys	Girls	Total
Nolla method	*r*	0958	0968	0956
	*p**	**<.001**	**<.001**	**<.001**
Cemeriere-European formula	*r*	0953	0961	0956
	*p**	**<.001**	**<.001**	**<.001**
Blenkin-Evans method	*r*	0958	0970	0964
	*p**	**<.001**	**<.001**	**<.001**

Note: Bold values mean statistically significant.
*Spearman correlation analysis.

value exceeded 1 only in the 14-year-old girls (MAE = 1.13 ± 0.7). In the overall sample, both the Nolla and Blenkin-Evans methods overestimated DA, whereas the Cameriere-European formula tended to underestimate it. Although the Blenkin-Evans method exhibited the highest accuracy rate within ±1 year, we prioritized MAE as the primary metric for evaluating estimation performance. MAE offers a continuous, direction-neutral measure of error that captures the average magnitude of deviation between estimated and actual ages across the full sample.[17,18] In contrast, the ±1 year threshold, while clinically intuitive, represents a binary classification that may mask subtle yet meaningful differences in accuracy among methods. Therefore, MAE was considered more suitable for detailed comparison and ranking of overall method performance.

The Cameriere-European formula, commonly used in age estimation, has undergone validation in multiple populations. According to a meta-analysis, this method typically tends to overestimate age in younger age groups, while slightly underestimating it in older children.[11] Our findings mirrored this trend: for both boys and girls aged 6–9 years, the formula produced minor overestimations, whereas for those aged 10–14, it showed slight underestimations. This pattern may be attributed to the regression line in the formula having an optimal intersection around age 10, with deviations in other age groups due to the limitations of the linear model. In a study on the Turkish population, Sezer and Çarikçioğlu[19] reported that the Cameriere-European formula underestimated CA by an average of 0.11 years, with its reliability varying across age groups, particularly decreasing in children over 11 years old. In a study focusing on children affected by molar incisor hypomineralization, Sezer et al.[20] observed no statistically significant differences in DA between children with molar incisor hypomineralization and healthy controls when using the Cameriere-European formula. This indicates that the method is robust even in the presence of certain developmental dental anomalies. Additionally, Gümüşboğa et al.[21] reported a high level of accuracy for this formula in children from Eastern Türkiye, with an average deviation of merely 0.1 years from the actual CA. Similarly, Yavuz et al.[22] found that although the formula generally underestimated age, its performance varied across age groups, with an overall mean underestimation of 0.35 years. In line with these studies, the current research also found a slight underestimation of age using the Cameriere-European formula: on average, −0.16 years in boys, −0.06 years in girls, and −0.11 years across the entire cohort. These outcomes support the reliability of the Cameriere-European formula for the Turkish

population, albeit with a minor underestimation tendency. Recalibrating the formula coefficients with local data could enhance its accuracy. Indeed, Kiş et al.[23] demonstrated that adapting the Cameriere-European formula using data from 1878 Turkish children aged 5–15 resulted in more precise age estimates, further supporting the importance of population-specific calibration.

The Blenkin-Evans method was introduced later than the other two methods and represents a modified version of the Demirjian technique. In the present study, based on MAE values, it ranked second in terms of accuracy. Chiam et al.[24] reported that the Blenkin-Evans method was valid for the Australian population; however, it tended to underestimate age in males while overestimating it in females. Similarly, a study conducted in the Sri Lankan population found that this method systematically underestimated CA across nearly all age and sex groups, with an average underestimation of 0.55 years.[25] In the Turkish population, Çarikçioğlu and Değirmenci[8] reported that the Blenkin-Evans method slightly underestimated CA by −0.09 years in females and −0.01 years in males, yielding highly accurate results with only a 0.05-year difference from CA in the overall sample. They also emphasized the method's particularly high accuracy in males. Şahin and Güleç[2] found that DA estimates using the Blenkin-Evans method closely aligned with CA, with an underestimation of 0.20 years in females and 0.12 years in males. In contrast, the present study found that the Blenkin-Evans method overestimated CA in females, males, and the overall sample (by 0.12, 0.14, and 0.13 years, respectively). Notably, the fact that the Blenkin-Evans standards—originally developed for a mixed Australian Aboriginal and Caucasian population—produced such small errors in Turkish children is remarkable. One possible explanation is that Blenkin and Evans revised the raw data from the Demirjian method to reduce systematic errors. This suggests that, when appropriately updated, the Demirjian method may retain validity across different populations. By correcting the biases present in the original Canadian sample with Australian data, the resulting model appears to partially align with the growth patterns of Turkish children. This observation may indicate that the Turkish population shares certain genetic or environmental growth characteristics with the studied Australian sample; however, further comprehensive comparative studies are needed to confirm this hypothesis.

The Demirjian method, based on dental calcification stages, is one of the oldest and most widely used radiographic techniques for DA estimation.[4] However, studies have shown that, beyond the original French-Canadian sample, the Demirjian method tends to overestimate CA in various populations, including Turkish children.[26,27] A meta-analysis on the Nolla method indicated that, although this approach generally underestimates age, it provides more accurate results compared to the Demirjian method.[28] Additionally, recent systematic reviews and meta-analyses have confirmed that the Nolla method typically underestimates age; however, some studies have reported that DA calculated using this method is closer to CA, particularly in girls.[28,29] Several studies conducted in different regions of Türkiye have also demonstrated that the Nolla method generally underestimates CA.[30–32] However, the extent of underestimation varies across regions. In the present study's Northwestern Anatolian sample, an evaluation of the accuracy of the Nolla method revealed that it overestimated CA by 0.31 years in boys and underestimated it by 0.25 years in girls. Although the overall sample showed a slight overestimation (0.04 years), the results were generally close to the actual age. The unexpected overestimation of age in boys suggests that the dental development of male children in Northwestern Anatolia may be more advanced compared to the population used as a reference in the Nolla method. This finding could be attributed to regional and socioeconomic differences.

Our findings underscore the practical significance of selecting an appropriate method for DA estimation. In forensic medicine, determining whether an individual has surpassed critical legal thresholds, such as 12 or 15 years, is of paramount importance.[33] For instance, if the Nolla method systematically underestimates CA, a 15-year-old individual might be incorrectly classified as 14 years old, potentially affecting their legal responsibilities. Similarly, in pediatric clinical practice, inaccurate age estimation during growth and development assessments may lead to suboptimal treatment planning. Therefore, selecting the method with the lowest error margin is crucial. However, the practical applicability of each method must also be taken into account depending on the clinical or forensic context. For instance, morphology-based techniques such as the Nolla and Blenkin-Evans methods offer faster and simpler visual assessments, which may be advantageous in busy clinical settings or public health programs. In contrast, the Cameriere-European formula, while more accurate, is relatively time-consuming due to its requirement for digital measurements and formula-based calculations. To address this limitation, the development and integration of artificial intelligence-driven tools or automated software may significantly reduce the time and effort involved, making it more suitable for routine use. Ultimately, method selection should be guided by the available technological resources, practitioner expertise, and the specific demands of the clinical or legal scenario.

This study has certain limitations. It is a retrospective, single-center study predominantly involving a patient population from the Northwestern Anatolia; therefore, the generalizability of the findings to the entire Turkish population is limited. Specifically, regional factors such as socioeconomic disparities, dietary habits, and environmental influences may have affected dental development in our sample, which could partially explain some of the observed

estimation deviations. Additionally, DA estimation was performed using existing reference tables from the literature. Future studies incorporating larger, population-specific samples to develop new regression equations could enhance the accuracy of these methods. Another limitation of the study is the exclusion of individuals aged 15 years and older, as DA estimation in this age group typically relies on methods based on third molar development. The observed variations in study results may stem from sample characteristics, methodological differences, or regional growth patterns. To better delineate regional differences within the country, large-scale, multicenter studies encompassing all geographical regions and evaluating factors such as socioeconomic status and nutrition in relation to dental development are warranted.

Conclusions

In this study, the Cameriere-European formula demonstrated the highest accuracy in DA estimation among Turkish children aged 6–14 years from Northwestern Anatolia, yielding significantly lower error rates compared to the Nolla and Blenkin-Evans methods. However, the Cameriere-European formula exhibited a slight tendency to underestimate CA. Overall, Cameriere-European formula and Blenkin-Evans method produced more consistent and less biased results than the Nolla method. These findings underscore the importance of selecting appropriate, population-specific, and up-to-date methods for forensic and clinical applications. In summary, there is no universally superior method for DA estimation; rather, identifying the most accurate approach for each specific population is crucial to improving reliability in age estimation practices.

Author contributions

B.Ç. and B.S. contributed to the study conception and design. B.Ç. and B.S. conducted the evaluation procedures and data collection. B.Ç. analyzed the data. B.Ç. and B.S. wrote the main manuscript text. All authors read and approved the final version of this paper.

Consent to participate

Written informed consent was obtained from the parents or legal guardians of all participants before their inclusion in the study.

Data availability

The data that support the findings of this study are available from the corresponding author (B.S.) upon reasonable requests.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethics approval

The study was conducted in accordance with the principles outlined in the Declaration of Helsinki for research involving human subjects. Ethical approval was obtained from the Clinical Research Ethics Committee of Çanakkale Onsekiz Mart University (Protocol No: 2021/04-11).

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