



A large sample-sized study on dental development of children treated at the Central Dental Clinic (OCEx) of the Brazilian Army

Marcos Vinicius Fernandes Machado^{1,2} · Mariana Quirino Silveira Soares² · Andrea Maia Sampaio Alonso Baz³ · Jose Luiz Cintra Junqueira² · Ademir Franco^{3,4} 

Received: 3 March 2022 / Accepted: 24 April 2022 / Published online: 29 April 2022
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2022

Abstract

Objectives To test and compare the performance of two radiographic methods for dental age estimation on a large sample of Brazilian boys and girls.

Material and methods The sample consisted of 1,990 panoramic radiographs of Brazilian children (age: 3–15.9 years) equally balanced based on sex. The sample was distributed into ten age categories, each with up to 200 children. Age estimation was performed with Willems' (2001) and Demirjian's (1973) methods. Estimated (EA) and chronological (CA) ages were compared. The performances of the methods were quantified based on sex and age category.

Results The overall differences between CA and EA for Willems' method in boys and girls were 0.06 and –0.02, respectively. For Demirjian's method, the differences were 0.60 and 0.74, respectively. The overestimations of Demirjian's method were statistically significant ($p < 0.001$). Willems' method reached the best outcomes among children between 3 and 12 years, while Demirjian's best performances were between the ages of 7 and 10 years.

Conclusion Willems' method led to differences between CA and AE that were acceptable for clinical and forensic practice. **Clinical relevance** Age estimation may guide clinical decisions based on treatment timing. Validating international tools is necessary to promote evidence-based practice and country-specific application. This study overcame the limitations of previous research to provide a more realistic perspective of the performance of age estimation methods in Brazilian children. Willems' method had a superior performance compared to Demirjian's method and led to outcomes that were better than most studies with the Brazilian population.

Keywords Age · Children · Dental development · Forensic dentistry · Imaging

Introduction

Estimating the biological age of patients is an important step in the treatment planning of orthodontics, special care dentistry, and oral medicine [1–4]. Other applications involve the forensic field, especially when it comes to the assessment

of the age of legal majority [5–8] and human identification [9–11]. Dental development plays a key role for age estimation of children and adolescents [12]. Studies advocate that the development of the human teeth can resist extrinsic and intrinsic factors, such as malnutrition [13], early/delayed extraction of deciduous teeth [14], and even systemic diseases [15].

Most of the dental age estimation techniques designed to assess dental development in children rely on radiographic analyses [16–20]. Operator-dependending procedures into the radiographic analyses include linear measurements of tooth ratios [21] and the classification of crown/root developmental stages [22–24]. Authors have demonstrated that staging techniques may be better than metric techniques [25]. In staging techniques, dental development is categorized into ordinal variables, and the stages are weighted into regression formulae, or maturity scores, to be converted in dental age [23].

✉ Ademir Franco
afrancodorosarioj001@dundee.ac.uk

¹ Central Dental Clinic (OCEx), Rio de Janeiro, Brazil

² Division of Oral Radiology, Faculdade Sao Leopoldo Mandic, Campinas, Brazil

³ Division of Forensic Dentistry, Faculdade Sao Leopoldo Mandic, Campinas, Brazil

⁴ Centre of Forensic and Legal Medicine and Dentistry, University of Dundee, Dundee, UK

The most popular technique developed to categorize developmental stages was proposed in 1973 by Demirjian et al. [23]. According to the authors, the seven permanent teeth of the left side of the mandible (3rd quadrant – except the third molar) can be classified into eight stages of crown/root formation [23]. The authors also provide a description of the stages to guide the operator during image analysis [23]. Some of Demirjian's stages are based on the appearance of specific anatomic features (i.e., molar radicular bifurcation in stage E); other stages are based on the proportion of root/crown sizes (i.e., “the root length is equal to or greater than the crown height” in stage F). After staging, Demirjian's method requires a conversion of dental development into self-weighted scores [23]. Further on, the scores are combined into a single maturity score that will lead to an estimated age (AE) [23]. Despite the recurrent use of Demirjian's technique in the scientific literature [26–30], studies have revealed consistent overestimations of the chronological age (CA) [31]. More specifically, a recent meta-analysis showed overestimations of 0.62 and 0.72 years in males and females, respectively [31].

In 2001, Willems et al. [32] performed an age estimation study with 2116 Belgian children to revisit Demirjian's approach and provide alternative self-weighted values [32]. In 2017, four meta-analyses confirmed Willems' method as reliable for age estimation [31, 33–35]. More recently, a meta-analysis [36] ranked Willems' method as the best for age assessment of Brazilian children. The outcomes, however, were based on a sample of nearly 900 individuals from the South region of Brazil [37], which does not necessarily represent the continental-size country and population. Other studies with Willems' method in the Brazilian population are available, but they have evident restrictions based on unbalanced [38] and small sample sizes [39, 40]. Others were designed case–control to study patients with systemic diseases [41, 42], and one tested the performance of a new statistical model [43].

An existing gap remains regarding the need for large sample-sized observational studies with balanced samples of Brazilian boys and girls. Equipped with over 60 dental offices and a centralized Oral Imaging and Diagnosis Unit, the Central Dental Clinic of the Brazilian Army (OCEx), in Rio de Janeiro/Brazil, provides nationwide dental treatment – figuring as an optimal source of panoramic radiographs for country-specific sample collection.

Based on the exposed, this study aimed to assess the dental development of Brazilian children from a large and balanced sample of panoramic radiographs collected from the Central Dental Clinic of the Brazilian Army (OCEx). Willems' and Demirjian's methods were used for dental age estimation.

Material and methods

Study model and ethical aspects

This was a cross-sectional study with retrospective sample collection. Ethical approval was obtained from the institutional committee of ethics in human research (protocol number: 43741421.0.0000.5374). The study was reported following the “*Enhancing the Quality and Transparency of Health Research*” (EQUATOR Network) considering the STROBE (*The Strengthening the Reporting of Observational Studies in Epidemiology*) checklist for cross-sectional studies [44].

Setting and participants

The sample consisted of panoramic radiographs ($n = 1,990$) equally obtained from Brazilian boys ($n = 995$) and girls ($n = 995$) between the years of 2008 and 2020 at the Central Dental Clinic (OCEx) of the Brazilian Army in Rio de Janeiro/Brazil. The sample was collected retrospectively from the Clinic's database, and the radiographs were exclusively obtained for clinical reasons. The inclusion criteria consisted of (a) Brazilian nationality; (b) age between 3 and 15.9 years; and (c) record of (at least) a panoramic radiograph in the OCEx's database. Exclusion criteria were (I) radiographs with bilaterally missing teeth in the mandible; (II) presence of extensive decay, restoration and root canal treatment bilaterally in the mandible (except third molars); (III) presence of visible bone lesions, surgical appliances in the mandible, deformation of maxillofacial bones, and visible dental anomalies; (IV) poor image quality; and (V) missing data about date of image acquisition and patient's date of birth and sex. Sample collection was performed between January and June 2021. The sample size established in the present study was set to reach as close as possible Willems' original sample size ($n = 2,116$) [32]. Additionally, the number of panoramic radiographs was set to be higher and more balanced based on age and sex compared to previous studies in Brazil [38–42]. The panoramic radiographs were imported to a personal computer equipped with a 15" screen and Adobe Photoshop CS6™ image viewer (Adobe Inc. San Jose, CA, USA) for magnification of 100% and eventual adjustments of brightness and contrast prior to analysis.

Variables and data sources

From each panoramic radiograph, the date of image acquisition was registered, as well as the patient's date of birth and sex. The difference between dates led to patient's CA. For methodological purposes, the CA was converted into categorical data by stratifying the sample into 10 age

categories: 3 | 7; 7 | 8; 8 | 9; 9 | 10; 10 | 11; 11 | 12; 12 | 13; 13 | 14; 14 | 15; and 15 | 16 years (Table 1). The analysis of the panoramic radiographs was performed in a dimmed room under standard viewing conditions [45]. No more than 25 radiographs were analyzed per day to avoid visual fatigue [46]. Dental age estimation followed the technique proposed by Demirjian et al. [23] through the classification of dental development into eight stages (A–H) (Fig. 1). The AE was obtained by converting Demirjian’s allocated stages into Willems’ scores for boys and girls [32]. Similarly, the same stages were converted into EA according to Demirjian’s original maturity scores and age conversion tables [23].

Table 1 Sample distribution based on sex and age categories

Age category	Boys	Girls	Total
3 7	95	95	190
7 8	100	100	200
8 9	100	100	200
9 10	100	100	200
10 11	100	100	200
11 12	100	100	200
12 13	100	100	200
13 14	100	100	200
14 15	100	100	200
15 16	100	100	200
3 16	995	995	1.990

Age expressed in years and sample size (n) distribution expressed in absolute values

Operator-dependent bias

The main observer was an orthodontist (12 years of experience) with a background (MSc) in oral radiology. In order to assess the consistency of the observer and reproducibility during image analysis, intra-observer agreement test was performed (re)assessing (T2) 100 panoramic radiographs within 30 days from the analysis of the original sample (T1). In parallel, an additional observer (oral radiology specialist) was recruited to assess the same 100 panoramic radiographs to enable inter-observer agreement. The two observers were supervised by a forensic odontologist with ten years of experience and background in dental age estimation studies. The rationale behind the number of radiographs ($n = 100$) that were re-assessed for examiner agreement tests was based on a previous dental age estimation study [47] that had a similar sample size ($n = 1.900$). The panoramic radiographs selected for intra- and inter-observer agreement tests had 700 teeth analyzed. Since image analysis consisted of the classification of dental developmental stages according to the technique of Demirjian et al. [23], a balanced selection of the total sample ($n = 1.990$ radiographs, $n = 13.930$ teeth of the third quadrant) was established. In this process, panoramic radiographs that were previously coded with alphanumeric identifiers were randomized (www.random.org) within each of the 10 age categories (resulting in 10 randomization steps). The first 10 panoramic radiographs ranked after randomization within each age category were selected for observer reproducibility tests. This strategy enabled a collection of radiographs from representatives (individuals) of all the age categories and in equal numbers. Consequently, all the available developmental stages were covered by the

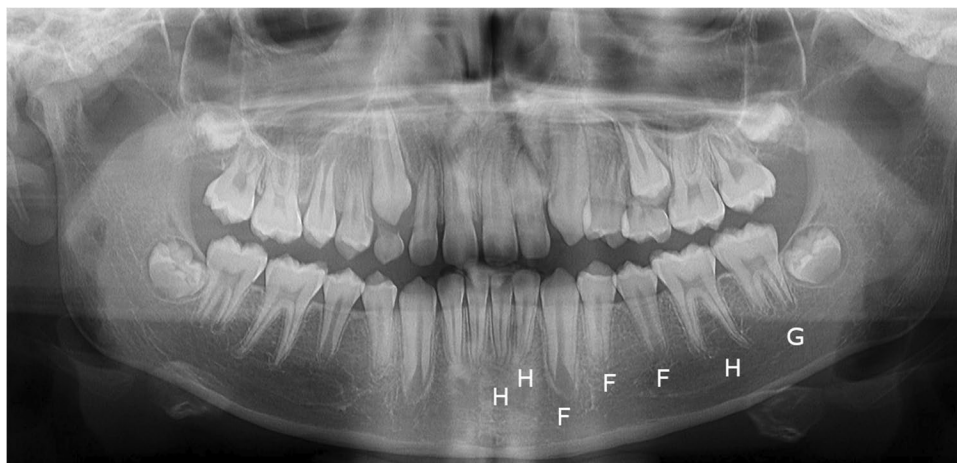


Fig. 1 Panoramic radiograph of a 11,5-year-old Brazilian boy that shows the seven mandibular left permanent teeth classified with Demirjian’s stages F, G, and H – in this case illustrating intermediate, advanced and terminal phases of root formation. According to Demirjian’s original description: in stage F (for incisors, canines and

premolars) the root length is equal or greater than the crown height; in stage G the walls of the root canal are now parallel, and their apical end is still partially open; in stage H the apical end is completely closed [23]

sample. Intra- and inter-observer agreements were quantified with Weighted Kappa statistics following previous studies in the field [37, 47, 48]. Both the intra- and inter-observer agreements were calculated individually for each of the teeth of the 3rd quadrant (except the third molar).

Quantitative variables and statistical methods

Data analysis was performed by means of descriptive and exploratory statistics of central tendency and dispersion. Shapiro–Wilk test was used to assess data normality regarding CA and EA. The comparison between CA and EA for each of the methods was accomplished with paired *t*-tests, intraclass correlation coefficient, and Bland–Altman approach. Additionally, the latter was used to assess the variation of CA and EA and to estimate the concordance intervals. The non-parametric methods of Kruskal and Dunn were used to assess the variation of AE across the 10 age categories, while Mann–Whitney’s test was used to assess variations between boys and girls. R software (R Foundation for Statistical Computing, Vienna, Austria) was used during statistical analyses. Statistical significance was set at 5%.

Results

Intra-observer agreement reached Weighted Kappa values of 1.0, 0.98, 0.94, 1.0, 0.97, 0.97, and 0.98 for the teeth #31, 32, 33, 34, 35, 36, and 37, respectively. For the same teeth, inter-observer agreement reached Weighted Kappa values of 0.97, 0.85, 0.81, 0.86, 0.80, 0.93, and 0.90, respectively. These results indicate almost perfect agreement (0.8–1.0) [49].

Shapiro–Wilk test revealed a normal distribution of the CA and of the EA (for Demirjian’s and Willems’ methods) ($p < 0.0001$).

The initial exploratory description of the sample revealed a mild overestimation of the CA using Willems’ method and a more evident overestimation from the application of Demirjian’s method in boys and girls (Table 2).

Bland–Altman’s approach showed a small bias between the EA from Willems’ method compared to the CA:

0.02 years (0.06 in boys and –0.02 in girls). The intraclass correlation coefficient outcome (0.97) suggested an excellent correlation between CA and EA [50]. For boys, girls and combined sex, there was a lack of statistically significant differences ($p > 0.05$) between CA and EA applying Willems’ method. Demirjian’s method, on the other hand, led to a considerably higher bias: 0.67 years (0.6 in boys and 0.74 in girls). Despite the excellent correlation between CA and EA (0.96), statistically significant differences were observed between CA and Demirjian’s EA for boys, girls, and both combined ($p < 0.0001$). Upper and lower limits of concordance for Bland–Altman approach in boys using Willems’ method were 1.98 and –1.87, respectively. In girls, the values were 1.95 and –1.99, respectively (Fig. 2). With Demirjian’s method, the upper and lower limits of concordance were 2.64 and –1.43 in boys and 2.70 and –1.23 in girls, respectively (Fig. 3).

Data analysis performed separately per age category revealed that the worse prediction by Willems’ method reached 0.38 in boys (age category: 13 | 14 years) and –0.33 in girls (age category: 14 | 15 years). Demirjian’s method reached median values up to 1.09 in boys (age categories: 13 | 14 and 14 | 15 years) and 1.45 in girls (age category: 11 | 12 years). Between the ages of 10 and 12, the differences between CA and EA were not only clinically significant (over 12 months) but also statistically significant ($p < 0.001$) (Table 3).

Discussion

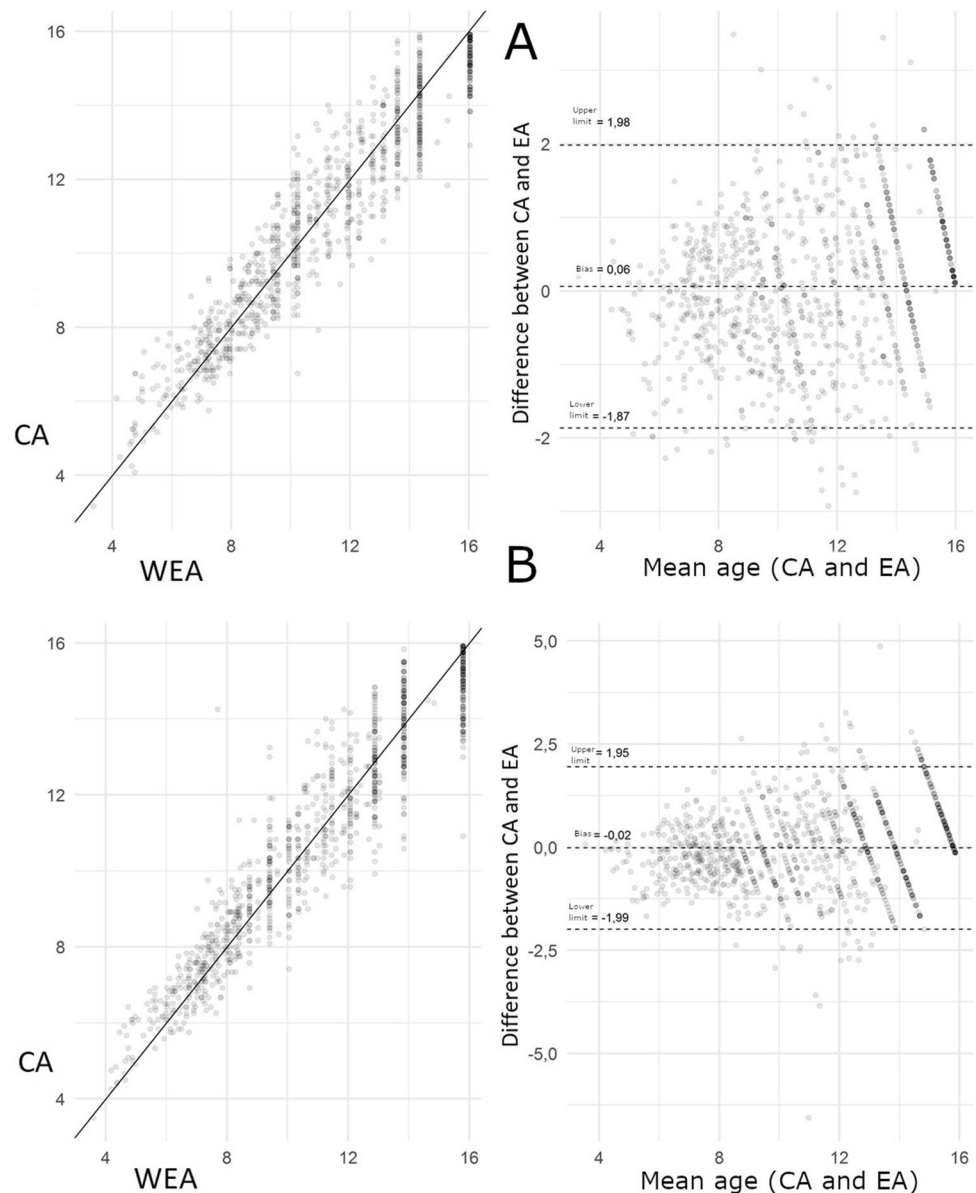
In the past, the biological age assessment for clinical purposes was mainly based on skeletal parameters, such as the radiographic growth markers of the hand and wrist [51–53]. Awareness of radiologic optimization and justification led to new methods based on the cervical vertebrae assessed from lateral cephalograms [54–56]. The use of age assessment tools for clinical purposes increased with studies on pubertal growth spurt correlating dental and skeletal parameters [4, 5]. However, knowledge of the best country-specific dental age estimation method is necessary prior to adding the

Table 2 Descriptive overview of the sample’s chronological age and the age estimated with Demirjian’s and Willems’ methods

Sex	Age (years)					
	CA		EA Willems		EA Demirjian	
	Mean (sd)	Median (min.; max.)	Mean (sd)	Median (min.; max.)	Mean (sd)	Median (min.; max.)
Boys	11.0 (2.9)	11.0 (3.2; 15.9)	11.1 (3.1)	10.9 (3.4; 16.0)	11.6 (3.1)	11.8 (3.7; 16.0)
Girls	10.9 (3.0)	10.9 (3.5; 15.9)	10.9 (3.2)	11.0 (3.6; 15.8)	11.6 (3.1)	11.5 (3.5; 16.0)
Total	11.0 (2.9)	11.0 (3.2; 15.9)	11.0 (3.1)	10.9 (3.4; 16.0)	11.6 (3.1)	11.6 (3.5; 16.0)

CA chronological age, EA estimated age, sd standard deviation, min. minimum, max. maximum

Fig. 2 Visual representation of the difference between Willems' (W) estimated age (EA) and the chronological age (CA) for boys (A) and girls (B). Mean difference between CA and EA: 0.06 in boys and -0.02 in girls



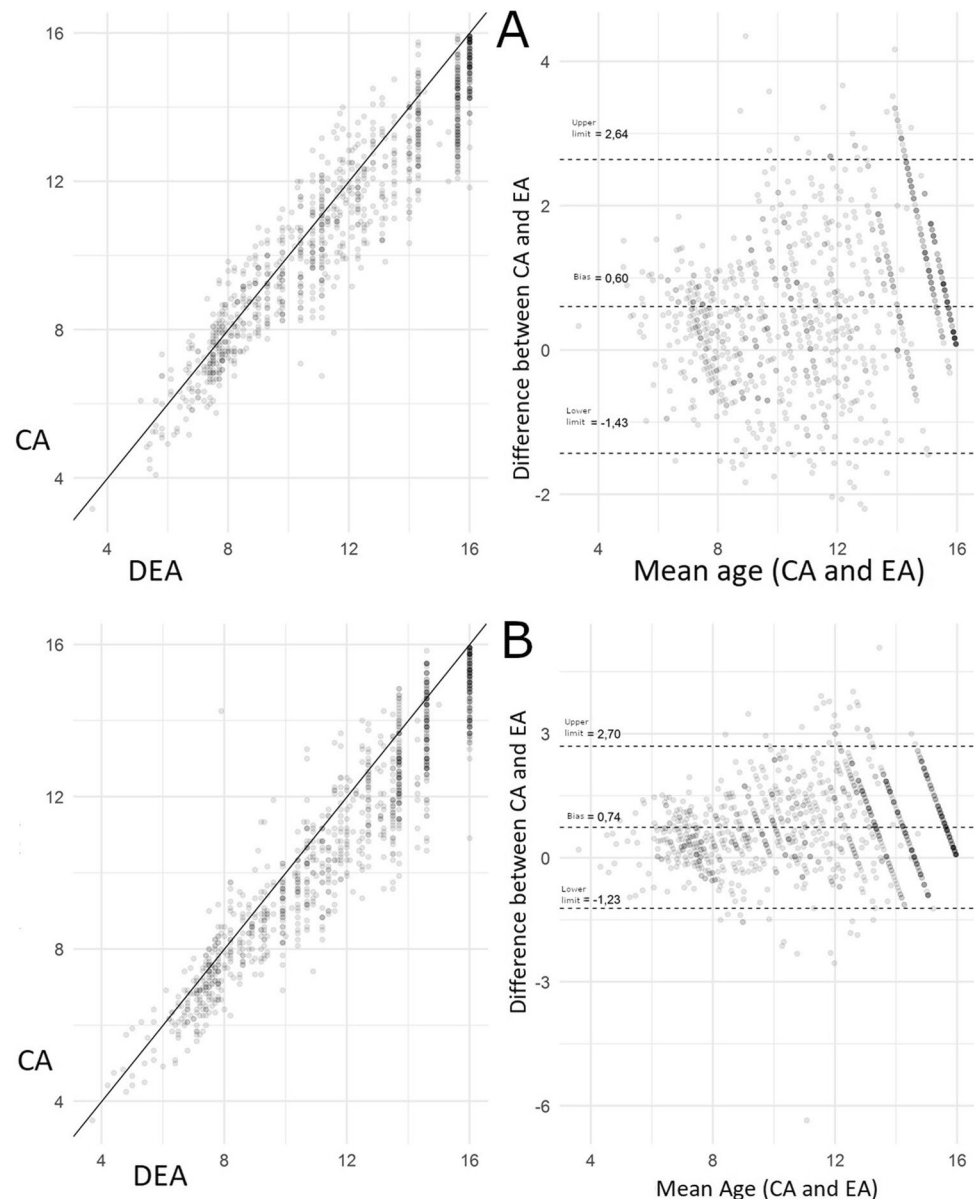
dental component to the study of biological age estimation. This large sample-sized observational study retrospectively assessed panoramic radiographs of a database in Brazil to test the performance of Willems' and Demirjian's methods for dental age estimation of boys and girls.

In 2021, a systematic literature review [36] screened dental age estimation methods applied in Brazilian children. According to the study, the seven methods that were meta-analyzed showed standardized mean differences between CA and EA of 0.05 years for Willems' method [32], -0.11 for Lilequist and Lundberg's [57], 0.22 for Nolla's [17], 0.27 for Mornstad's [58], -0.31 for Cameriere's [21], 0.74 for Demirjian's (seven teeth version) [23], and -0.87 for Haavikko's [59]. The outcomes of the present study are consistent with the current scientific literature, showing a

variation between CA and EA of 0.02 years for Willems' method and 0.67 for Demirjian's method (boys and girls pooled together).

From a global perspective, the performances of Willems' and Demirjian's methods have a similar pattern. A systematic literature review and meta-analysis published in 2017 [31] revisited articles that used Willems' and/or Demirjian's methods in children worldwide. The authors found statistically significant overestimations of Demirjian's method in boys and girls ($p < 0.05$) – an outcome that converges with our findings. The overall overestimations for boys and girls, considering all the meta-analyzed studies, were 0.62 and 0.72 years, respectively [31]. In our study, the overall overestimations were 0.60 years for boys and 0.74 years for girls. These outcomes highlight limitations of

Fig. 3 Visual representation of the difference between Demirjian's (D) estimated age (EA) and the chronological age (CA) for boys (A) and girls (B). Mean difference between CA and EA: 0.6 in boys and 0.74 in girls



Demirjian's method in practice since overestimation between 7 and 9 months may be clinically significant depending on the diagnostic/therapeutic need. From a forensic perspective, methods that lead to overestimations of nearly 1 year should be carefully considered as well – since they could categorize a child as an adolescent or even allocate a boy/girl into the legal age of sexual consent (i.e. > 14 years in Brazil). For Willems' method, the overall overestimations for boys and girls reported in the literature are below 0.29 years (or 3.5 months) – a value that may be both clinically and forensically acceptable in most scenarios [31]. Contrasting, the performance of Willems' method in our study was considerably superior, reaching overall overestimations of only 0.06 years (nearly 21 days in boys). These outcomes confirm Willems' method as a proper dental age estimation tool to

assess the biological age of Brazilian boys and girls. Moreover, our findings validate the improvements made by Willems et al. [32] after revisiting Demirjian's technique [23] in 2001 – since overestimations were drastically reduced.

A deeper look into data stratified based on age categories shows that the best performances of both methods occurred within young age categories. Willems' method [32] performed better in children with ages between 3 and 12 years, in which the difference between CA and EA was not higher than 0.13 years (boys and girls combined). Demirjian's method [23] had better performances in children between 7 and 10 years, in which the difference between CA and EA was below 0.65 years. In Demirjian's outcomes, more specifically, the difference between CA and EA is more evident since statistically significant differences ($p < 0.05$) were

Table 3 Differences between chronological and estimated ages for Willems' and Demirjian's method for boys and girls in each of the age categories

CA vs	Age	n	Boys	Girls	Combined	p	
Willems' EA	3 7	190	0.04 (−1.98; 3.49) ^a	−0.10 (−1.68; 1.82) ^a	−0.05 (−1.98; 3.49)	0.272	
	7 8	200	0.00 (−2.27; 3.01) ^a	−0.16 (−1.35; 2.63) ^a	−0.10 (−2.27; 3.01)	0.202	
	8 9	200	0.18 (−2.18; 1.91) ^a	−0.27 (−1.12; 1.80) ^a	−0.09 (−2.18; 1.91)	0.026	
	9 10	200	−0.04 (−2.09; 2.88) ^a	−0.26 (−2.38; 2.96) ^a	−0.15 (−2.38; 2.96)	0.352	
	10 11	200	−0.18 (−1.77; 2.78) ^a	0.06 (−1.64; 4.87) ^a	−0.06 (−1.77; 4.87)	0.340	
	11 12	200	−0.21 (−2.01; 3.45) ^a	0.19 (−2.93; 2.34) ^a	0.13 (−2.93; 3.45)	0.142	
	12 13	200	0.31 (−2.71; 3.11) ^a	0.10 (−1.69; 1.42) ^a	0.22 (−2.71; 3.11)	0.204	
	13 14	200	0.38 (−2.93; 2.20) ^a	0.01 (−3.84; 2.79) ^a	0.17 (−3.84; 2.79)	0.206	
	14 15	200	−0.16 (−2.74; 1.78) ^a	−0.33 (−6.56; 1.79) ^a	−0.16 (−6.56; 1.79)	0.232	
	15 16	200	0.28 (−2.16; 1.03) ^a	0.12 (−1.99; 0.79) ^a	0.21 (−2.16; 1.03)	0.012	
	P			0.1049	0.2460		
	Demirjian's EA	3 7	190	0.67 (−0.98; 4.35) ^{cd}	0.60 (−0.95; 2.98) ^{bcde}	0.66 (−0.98; 4.35)	0.440
		7 8	200	0.31 (−1.53; 3.58) ^d	0.36 (−0.75; 3.48) ^{de}	0.33 (−1.53; 3.58)	0.211
		8 9	200	0.23 (−1.53; 2.77) ^{cd}	0.52 (−0.78; 2.95) ^{bcde}	0.44 (−1.53; 2.95)	0.041
		9 10	200	0.37 (−1.83; 3.37) ^{cd}	0.89 (−1.55; 3.92) ^{abc}	0.65 (−1.83; 3.92)	0.012
10 11		200	0.47 (−1.75; 3.67) ^{abcd}	1.09 (−1.48; 5.08) ^a	0.73 (−1.75; 5.08)	<0.001	
11 12		200	0.42 (−1.53; 4.17) ^{bcd}	1.45 (−2.32; 3.13) ^a	0.80 (−2.32; 4.17)	<0.001	
12 13		200	0.76 (−2.03; 3.52) ^{abc}	1.03 (−0.70; 2.22) ^{ab}	0.92 (−2.03; 3.52)	0.630	
13 14		200	1.09 (−2.13; 2.60) ^a	0.77 (−2.55; 3.00) ^{abcd}	0.90 (−2.55; 3.00)	0.119	
14 15		200	1.09 (−2.20; 1.75) ^{ab}	0.39 (−6.35; 2.00) ^{cde}	0.93 (−6.35; 2.00)	0.031	
15 16		200	0.42 (−1.45; 1.00) ^{cd}	0.33 (−1.23; 1.00) ^e	0.33 (−1.45; 1.00)	0.393	
P				<0.001	<0.001		

n absolute sample size, CA chronological age, EA estimated age, Combined boys and girls pooled together. Equal superscript letters across lines indicate a lack of statistically significant differences between the medians of the age categories; p: paired t-test; Bold values: p < 0.05

found between age intervals. A reasonable explanation for this phenomenon is the reduced number of developing teeth over time. Consequently, dental age estimation is performed based on restricted dental age information available. The scientific literature corroborates this phenomenon by showing a vast number of dental age estimation studies that sample individuals below the age of 16 years [31, 38, 43]. Moreover, Demirjian et al. [23] advertise that their method is applicable to children between 3 and 17 years. Older individuals would have all the seven mandibular left permanent teeth in stage H (complete apical formation) and would lose reference for proper age estimation.

One of the inherent limitations of Willems' and Demirjian's methods, as well as most of the existing dental age estimation methods based on radiographic analysis, is the operator-dependent procedure to allocate dental stages to developing teeth – which is subjective. Despite the almost excellent intra- and inter-observer agreement detected in this study, the performance of the methods could be biased by operator performance. This is one of the reasons that could explain the lower error rates detected in the present study compared to previous investigations of Willems' method [31], for instance. Future studies in the field should focus

on reducing operator-dependent procedures with automation tools, such as artificial intelligence. Machine learning fed with big-data seems to be the next step in dental age estimation studies.

In this large sample-sized observational study, Willems' method had evidently superior performance compared to Demirjian's method for dental age estimation. The reliability of the present evidence is supported by the methodological decisions that enhanced the protocols of country-specific studies that were limited in the past.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00784-022-04511-z>.

Declarations

Ethics approval All applicable international, national, and/or institutional guidelines for the care and use of animals were followed. Ethical approval was obtained from the Ethics Committee of Human Research of Faculdade Sao Leopoldo Mandic, Brazil (protocol number: 43741421.0.0000.5374).

Informed consent For this type of study (observational with retrospective data collection from existing databases), informed consent is not required.

Conflict of interest The authors declare no competing interests.

References

- Possagno LP, Franco A, Paranhos LR, Grando LJ, De Lima AAS, Bezerra ISQ, Fernandes A (2018) Morphological analysis of the skeletal development in lateral cephalometric radiographs of HIV infected children ongoing Highly Active Antiretroviral Therapy. *Med Oral Patol Oral Cir Bucal* 23:e691-697. <https://doi.org/10.4317/medoral.22610>
- Pinchi V, Bianchi I, Pradella F, Vitale G, Focardi M, Tonni I, Ferrante L, Bucci A (2021) Dental age estimation in children affected by juvenile rheumatoid arthritis. *Int J Legal Med* 135:619–629. <https://doi.org/10.1007/s00414-020-02395-w>
- Aguiar LBV, Caldas MP, Haiter Neto F, Ambrosano GMB (2013) A methodology to measure cervical vertebral bone maturation in a sample from low-income children. *Braz Dent J* 24:30–34. <https://doi.org/10.1590/0103-6440201301787>
- Bittencourt MV, Cericato G, Franco A, Girão R, Lima APB, Paranhos L (2018) Accuracy of dental development for estimating the pubertal growth spurt in comparison to skeletal development: a systematic review and meta-analysis. *Dentomaxillofac Radiol* 47:20170362. <https://doi.org/10.1259/dmfr.20170362>
- Cericato GO, Franco A, Bittencourt MA, Nunes MA, Paranhos LR (2016) Correlating skeletal and dental developmental stages using radiographic parameters. *J Forensic Leg Med* 42:13–18. <https://doi.org/10.1016/j.jflm.2016.05.009>
- Franco A, Vetter F, Coimbra EF, Fernandes A, Thevissen P (2020) Comparing third molar root development staging in panoramic radiography, extracted teeth, and cone beam computed tomography. *Int J Legal Med* 134:347–353. <https://doi.org/10.1007/s00414-019-02206-x>
- Sartori V, Franco A, Linden MS, Cardoso M, Castro D, Sartori A, Silva C, Trentin M, De Carli JP (2021) Testing international techniques for the radiographic assessment of third molar maturation. *J Clin Exp Dent* 13:e1182-1188. <https://doi.org/10.4317/jced.58916>
- Franco RPAV, Franco A, Turkina A, Arakelyan M, Arzukanyan A, Velenko P, Bortolami PB, Makeeva I, da Silva RHA (2021) Radiographic assessment of third molar development in a Russian population to determine the age of majority. *Arch Oral Biol* 125:105102. <https://doi.org/10.1016/j.archoralbio.2021.105102>
- Adserias-Garriga J, Thomas C, UBelaker DH, Zapico SC (2018) When forensic odontology met biochemistry: Multidisciplinary approach in forensic human identification. *Arch Oral Biol* 87:7–14. <https://doi.org/10.1016/j.archoralbio.2017.12.001>
- Vodanović M, Dumančić J, Galić I, Savić Pavićin I, Petrovečki M, Cameriere R (2011) Brkić H (2011) Age estimation in archaeological skeletal remains: evaluation of four non-destructive age calculation methods. *J Forensic Odontostomatol* 29:14–21
- Matteussi GT, Jacometti V, Franco A, Silva RHA (2022) Age estimation in humans through the analysis of aspartic acid racemization from teeth: A scoping review of methods, outcomes, and open research questions. *Forensic Sci Int* 331:111154. <https://doi.org/10.1016/j.forsciint.2021.111154>
- Adserias-Garriga J (2019) Age estimation: a multidisciplinary approach. Academic Press, London
- Elamin F, Liversidge H (2013) Malnutrition has no effect on the timing of human tooth formation. *PLoS ONE* 8:e72274. <https://doi.org/10.1371/journal.pone.0072274>
- Fanning EA (1962) Effect of extraction of deciduous molars on the formation and eruption of their successors. *Angle Orthodont* 32:44–53. [https://doi.org/10.1043/0003-3219\(1962\)032%3C0044:EOEODM%3E2.0.CO;2](https://doi.org/10.1043/0003-3219(1962)032%3C0044:EOEODM%3E2.0.CO;2)
- Bezerra ISQ, Topolski F, França SN, Brucker MR, Fernandes A (2015) Assessment of skeletal and dental ages of children and adolescents with type 1 Diabetes Mellitus. *Braz Oral Res* 29:1–5. <https://doi.org/10.1590/1807-3107BOR-2015.vol29.0025>
- Moorrees CF, Fanning EA, Hunt E Jr (1963) Age variation of formation stages for ten permanent teeth. *J Dent Res* 42:1490–1502. <https://doi.org/10.1177/00220345630420062701>
- Nolla CM (1960) The development of the permanent teeth. *J Dent Child* 27:254–266
- Nicodemo RA, Moraes LC, Médici FE (1974) [Tabela cronológica da mineralização dos dentes permanentes entre brasileiros]. *Rev Fac Odont São José dos Campos* 3:55–56. [Portuguese]
- Roberts GJ, Parekh S, Petrie A, Lucas VS (2008) Dental age assessment (DAA): a simple method for children and emerging adults. *Br Dent J* 204:E7. <https://doi.org/10.1038/bdj.2008.21>
- Anderson DL, Thompson GW, Popovich F (1976) Age of attainment of mineralization stages of the permanent dentition. *J Forensic Sci* 21:191–200
- Cameriere R, Ferrante L, Cingolani M (2006) Age estimation in children by measurement of open apices in teeth. *Int J Leg Med* 120:49–52. <https://doi.org/10.1007/s00414-005-0047-9>
- Demirjian A, Goldstein H (1976) *Ann Hum Biol* 3(5):411–21. <https://doi.org/10.1080/03014467600001671>
- Demirjian A, Goldstein H, Tanner JM (1973) A new system of dental age assessment. *Hum Biol* 45:211–227
- AlQahtani SJ, Hector MP, Liversidge HM (2010) Brief communication: The London atlas of human tooth development and eruption. *Am J Phys Anthropol* 142(3):481–490. <https://doi.org/10.1002/ajpa.21258>
- Thevissen P, Fieuws S, Willems G (2011) Third molar development: Measurements versus scores as age predictor. *Arch Oral Biol* 56:1035–1040. <https://doi.org/10.1016/j.archoralbio.2011.04.008>
- Eid RMR, Simi R, Friggi MNP, Fisberg M (2002) Assessment of dental maturity of Brazilian children aged 6 to 14 years using Demirjian's method. *Int J Paediatr Dent* 12:423–428. <https://doi.org/10.1046/j.1365-263x.2002.00403.x>
- De Donno A, Angrisani C, Mele F, Introna F, Santoro V (2021) Dental age estimation: Demirjian's versus the other methods in different populations. A literature review. *Med Sci Law* 61:125–129. <https://doi.org/10.1177/0025802420934253>
- Han MQ, Chu G, Chen T, Zhou H, Guo YC (2019) Research progress of age estimation based on the Demirjian's method. *Fa Yi Xue Za Zhi* 35:737–743. <https://doi.org/10.12116/j.issn.1004-5619.2019.06.017>
- Fei Y, Yang L, Sheng K, LAi G, Wang J (2021) Dental maturation in a Chinese sample using Demirjian method. *Ann Human Biol* 48:393–399. <https://doi.org/10.1080/03014460.2021.1988705>
- Lan LM, Yang ZD, Sun SL, Wen D, Kureshi A, Zeye MMJ, Zha L, Li M (2019) Application of Demirjian's and Cameriere's method in dental age estimation of 8–16 year old adolescents from Hunan Han nationality. *Fa Yi Xue Za Zhi*. 35:406–410. <https://doi.org/10.12116/j.issn.1004-5619.2019.04.005>
- Esan TA, Yengopal V, Schepartz LA (2017) The Demirjian versus the Willems method for dental age estimation in different populations: A meta-analysis of published studies. *PLoS One* 12:e0186682. <https://doi.org/10.1371/journal.pone.0186682>
- Willems G, Van Olmen A, Spiessens B, Carels C (2001) Dental age estimation in Belgian children: Demirjian's technique revisited. *J Forensic Sci* 46:893–895
- Yusof MYPM, Mokhtar IW, Rajasekharan S, Overholser R, Martens L (2017) Performance of Willem's dental age estimation method in children: A systematic review and meta-analysis. *Forensic Sci Int* 280:1-245.e10. <https://doi.org/10.1016/j.forsciint.2017.08.032>

34. Sehrawat JS, Singh M (2017) Willems method of dental age estimation in children: A systematic review and meta-analysis. *J Forensic Leg Med* 52:122–129. <https://doi.org/10.1016/j.jflm.2017.08.017>
35. Wang J, Ji F, Zhai Y, Park H, Tao J (2017) Is Willems method universal for age estimation: A systematic review and meta-analysis. *J Forensic Leg Med* 52:130–136. <https://doi.org/10.1016/j.jflm.2017.09.003>
36. Franco A, Oliveira MN, Vidigal MTG, Blumenberg C, Pinheiro AA, Paranhos LR (2021) Assessment of dental age estimation methods applied to Brazilian children: a systematic review and meta-analysis. *Dentomaxillofac Radiol* 50:20200128. <https://doi.org/10.1259/dmfr.20200128>
37. Franco A, Thevissen P, Souza PHC, Fieuws S, Willems G (2013) Applicability of Willems model for dental age estimations in Brazilian children. *Forensic Sci Int* 231:401.e1–401.e4. <https://doi.org/10.1016/j.forsciint.2013.05.030>
38. Fritola M, Fujikawa AS, Ferreira FM, Franco A, Fernandes A (2015) Estimativa de idade dental em crianças e adolescentes brasileiros comparando os metodos de Demirjian e Willems. *Rev Bras Odontol Legal RBOL* 2:26–34. <https://doi.org/10.21117/rbol.v2i1.18> ([Portuguese])
39. Machado ALR, Borges BS, Cameriere R, Machado CEP, Silva RHA (2020) Evaluation of Cameriere and Willems age estimation methods in panoramic radiographs of Brazilian children. *J Forensic Odontostomatol* 38:8–15
40. Gonçalves LS, Machado ALR, Gaeta-Araujo H, Recalde TSF, Oliveira-Santos C, Silva RHA (2021) A comparison of Demirjian and Willems age estimation methods in a sample of Brazilian non-adult individuals. *Forensic Imag* 25:200456. <https://doi.org/10.1016/j.fri.2021.200456>
41. Souza RB, Assunção LRS, Franco A, Zaroni FM, Holderbaum RM, Fernandes A (2015) Dental age estimation in Brazilian HIV children using Willems' method. *Forensic Sci Int* 257:e1–510.e4. <https://doi.org/10.1016/j.forsciint.2015.07.044>
42. Gabardo G, Maciel JVB, Franco A, Lima AAS, Costa TRF, Fernandes A (2020) Radiographic analysis of dental maturation in children with amelogenesis imperfecta: A case-control study. *Spec Care Dent* 40:267–272. <https://doi.org/10.1111/scd.12456>
43. Rocha LT, Ingold MS, Panzarella FK, Santiago BM, Oliveira RN, Bernardino IM, Makeeva I, Junqueira JLC, Franco A (2022) Applicability of Willems method for age estimation in Brazilian children: performance of multiple linear regression and artificial neural network. *Egypt J Forensic Sci* 12:9. <https://doi.org/10.1186/s41935-022-00271-9>
44. Von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP, STROBE Initiative (2008) The Strengthening the reporting of observational studies in epidemiology (STROBE) statement: guidelines for reporting observational studies. *J Clin Epidemiol* 61:344–349. <https://doi.org/10.1016/j.jclinepi.2007.11.008>
45. Vasconcelos KF, Nicolielo LFP, Nascimento MC, Haiter-Neto F, Bóscolo FN, Van Dessel J, EzEldeen M, Lambrichts I, Jacobs R (2015) Artefact expression associated with several cone-beam computed tomographic machines when imaging root filled teeth. *Int Endod J* 48:994–1000. <https://doi.org/10.1111/iej.12395>
46. Nascimento EHL, Gaêta-Araujo H, Vasconcelos KF, Freire BB, Oliveira-Santos C, Haiter-Neto F, Freitas DQ (2018) Influence of brightness and contrast adjustments on the diagnosis of proximal caries lesions. *Dentomaxillofac Radiol* 47:20180100. <https://doi.org/10.1259/dmfr.20180100>
47. Altalie S, Thevissen P, Fieuws S, Willems G (2014) Optimal dental age estimation practice in United Arab Emirates' children. *J Forensic Sci* 59:383–385. <https://doi.org/10.1111/1556-4029.12351>
48. Yusof MYPM, Thevissen PW, Fieuws S, Willems G (2014) Dental age estimation in Malay children based on all permanent teeth types. *Int J Legal Med* 128:329–333. <https://doi.org/10.1007/s00414-013-0825-8>
49. Landis JR, Koch GG (1977) The measurement of observer agreement for categorical data. *Biometrics* 33:159–174
50. Szklo M, Nieto FJ (2018) *Epidemiology beyond the basis*, 4th edn. Jones and Bartlett Publishers, Burlington p 578
51. Greulich WW, Pyle SI (1950) *Radiographic atlas of skeletal development of the hand and wrist*. Stanford University Press, Stanford
52. Eklöf O, Ringertz H (1967) A method for assessment of skeletal maturity. *Ann Radiol* 10:330–336
53. Tanner JM, Whitehouse RH, Healy MJR (1962) A new system for estimating skeletal maturity from the hand and wrist, with standards derived from a study of 2600 healthy british children. International Children's Centre, Paris
54. Hassel B, Farman AG (1995) Skeletal maturation evaluation using cervical vertebrae. *Am J Orthod Dentofacial Orthop* 107:58–66. [https://doi.org/10.1016/s0889-5406\(95\)70157-5](https://doi.org/10.1016/s0889-5406(95)70157-5)
55. Baccetti T, Franchi L, McNamara JA Jr (2005) The cervical vertebral maturation (CVM) method for the assessment of optimal treatment timing in dentofacial orthopedics. *Semin Orthod* 11:119–129. <https://doi.org/10.1053/j.sodo.2005.04.005>
56. Seedat AK, Forsberg CD (2005) An evaluation of the third cervical vertebra (C3) as a growth indicator in Black subjects. *SADJ* 60(156):158–160
57. Liliequist B, Lundberg M (1971) Skeletal and tooth development – a methodologic investigation. *Acta Radiol Diagn* 11:97–112
58. Mörnstad H, Staaf V, Welander U (1994) Age estimation with the aid of tooth development: a new method based on objective measurements. *Scand J Dent Res* 102:137–143. <https://doi.org/10.1111/j.1600-0722.1994.tb01169.x>
59. Haavikko K (1974) Tooth formation age estimated on a few selected teeth – a simple method for clinical use. *Proc Finn Dent Soc* 70:15–19

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.