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ORIGINAL RESEARCH

A comparison of estimated age based on pulp volume from cone beam computed tomography (CT) images and panoramic radiography data with chronological age

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Abstract

This retrospective study was conducted to evaluate different methods for dental age estimation in children and to examine the feasibility of using cone beam computed tomography (CBCT) data for age estimation. A total of 200 radiographic records (both digital panoramic radiographs and CBCTs) were acquired from 100 children aged 9 to 16 years, all taken on the same dates. Radiographic data was acquired from archived records and included both panoramic radiography and CBCT data belonging to the same individual. CBCT was used when panoramic radiographic data was insufficient. The pulp volume and pulp/tooth volume ratio of the left first molar teeth in the mandible were calculated from the CBCT data using MIMICS software. In addition, age was estimated by the Demirjian and Willems methods from data obtained from panoramic radiography images. Statistical analyses and linear regression analysis were performed as necessary. There was a statistically significant difference between the mean difference between the Demirjian method and chronological age, and between the Willems method and chronological age ($p < 0.001$). Statistically significance was achieved in a linear regression model created from pulp volume ($R^2 = 0.098$) and pulp/tooth volume ratio ($R^2 = 0.395$) data for the estimated dental age analysis ($p < 0.001$) and a negative correlation was observed with chronological age. When compared estimated dental age from CBCT data with chronological age, the pulp/tooth volume ratio method yielded results closer to chronological age than using only pulp volume data. When considering both panoramic radiographic age estimation methods and age estimation methods using CBCT data, we found that the results obtained with the Willems method, a panoramic radiographic age estimation technique, provided the closest results to the chronological age. More contributions should be made to the literature regarding the feasibility of age estimation using pulp and tooth volume as an alternative method.

Keywords

Cone beam computed tomography; Age determination; Pulp volume; Tooth volume; MIMICS; Panoramic radiography

1. Introduction

Accurate age estimation is of paramount importance in forensic science [1]. Age adjustments play a crucial role in criminal proceedings, clinical research, the identification of remains, the formation of clinical treatment plans, and many other areas [2]. Age estimation relies on a range of indicators, such as the growth and development patterns observed in bones and teeth, variations in weight and height, the onset of puberty, and markers of psychological development. Notably, estimated dental age analysis, encompassing both morphological and radiological assessments of teeth, extends beyond the realm of forensic dentistry, and plays a pivotal role in human anthropology [3]. Various methodologies have been established for dental age estimation, including morphological, histological, and radiographic techniques [4]. Among the most prevalent are methods such are those developed by Demirjian [4], Willems [5], and Cameriere [6], which evaluate dental development phases using panoramic and periapical radiographs. Age estimation often relies on panoramic radiographs, utilizing methods such as that described by Demirjian and its modified version, the Willems method. However, two-dimensional images can occasionally be inadequate in conveying volumetric information about tooth-related structures. This limitation underscores the growing importance of emerging three-dimensional imaging technologies. The use of cone beam computer tomography (CBCT) reduces the superposition of anatomical components by providing coronal, sagittal, and axial slices. This data can help the clinician to understand three-dimensional morphological features [7–9]. In recent times, the use of CBCT images for age estimation has gained significant traction, primarily due to its ability to provide detailed data relating to pulp and tooth volume. CBCT can also be applied across diverse samples and mitigates issues related to magnification and distortion. Measurements of tooth and pulp volume in three-dimensional (3D) images captured by CBCT are typically processed using specialized software, such as MIMICS [10].

In this study, we aimed to measure and evaluate pulp and tooth volume from CBCT images in the pediatric population using MIMICS software. We also investigated the potential of using pulp and tooth volume data for age estimation. Furthermore, we sought to juxtapose the precision of these findings against age estimates derived from the Demirjian and Willems methods, utilizing panoramic radiographs taken concurrently from the same patient cohort, and to compare these with their actual chronological age.

2. Materials and methods

In this retrospective study, a total of 200 radiographic records, including both digital panoramic radiographs and CBCTs, were included from 100 children aged 9 to 16 years who had received dental treatment at Dicle University Faculty of Dentistry. Our archived records, constituting our radiographic data, consisted of both panoramic radiography and CBCT data belonging to the same individual. CBCT was used in cases where the panoramic radiographic data was insufficient for diagnosis and treatment. No radiographs were taken from any individual solely for the purpose of estimated dental age analysis. Radiographic analyses were conducted by two experienced pediatric dental specialists. Conducted between March 2022 and February 2023, this research used the MIMICS software (MIMICS Research 20.0, Materialise, Leuven, Belgium) to compute the pulp and tooth volume of the mandibular left permanent 1st molars from the CBCT data. Both the pulp volume and the pulp-to-tooth volume ratio were assessed for dental age estimation. Panoramic radiographs were evaluated based on the mineralization stages of the permanent teeth in the mandible, using scoring tables from both the Demirjian and Willems methods. Chronological age was determined by subtracting the date-of-birth from the date the radiograph was taken.

2.1 Inclusion criteria

The inclusion criteria were as follows: (1) the patient was in the mixed and/or permanent dentition period; (2) completion of apexogenesis in the included mandibular left permanent 1st molars; (3) no root canal treatment or tooth extraction procedures, no decay, fillings, or veneer crowns on mandibular permanent molars; (4) absence of any pathology in the mandibular permanent molars and surrounding tissues, and (5) possession of both radiographic data (CBCT and panoramic radiography) and belonging to the pediatric age group.

2.2 Exclusion criteria

The exclusion criteria were as follows: (1) positional anomalies, absence or impaction of the evaluated mandibular molars; (2) incomplete apex development of the evaluated mandibular molars; (3) presence of any decay, restoration and/or root-canal filling, fractures, or periapical pathology in the evaluated mandibular molars, and (4) the existence of pulp stones, pulp calcification, and other developmental or morphological anomalies in the evaluated mandibular molars.

2.3 Data collection and evaluation

All digital panoramic films (Progeny, Midmark Company, USA) were taken using a panoramic x-ray machine with 0.5 mm focal point, 3.2 mm filtration, 70 kVp, 10 mA and 15.9 s scan parameters. All CBCT images were obtained using an imaging device (i-CAT®, Model 17–19, Imaging Sciences International, Hatfield, PA, USA) with 120 kvp, 5 mA, 8.9 seconds, a 16 × 13 cm imaging field, and 0.30 mm^3 isotropic voxels with 0.3 mm slice thickness. Acquired images were saved in DICOM (Digital Imaging and Communications in Medicine) format. Radiographic evaluations were performed on a computer with 1920 × 1080 pixel resolution, an HP Envy 13-ah1xxx model with an Intel Core i7 processor, and a 13.3-inch screen size.

2.4 Application of the Demirjian method

According to the Demirjian method, developmental stages that were created separately for each tooth (Fig. 1) were taken as the basis; then, we collated numerical values generated by matching these stages to scores using separate tables prepared for male and female individuals (Tables 1,2), thereby obtaining the individual's current maturity score [4]. The total score ranged between 0 and 100, and after calculating the individual's current score, the estimated dental age of the individual was determined by referring to the maturity score table for the specific gender and matching the corresponding age range (Tables 3,4).

TABLE 1. Scoring table for the Demirjian method for males [4].

Tooth	A	B	C	D	E	F	G	H
M_2	2.1	3.5	5.9	10.1	12.5	13.2	13.6	15.4
M_1	…	…	0	8.0	9.6	12.3	17.0	19.3
PM_2	1.7	3.1	5.4	9.7	12.0	12.8	13.2	14.4
PM_1	…	0	3.4	7.0	11.0	12.3	12.7	13.5
C	…	…	0	3.5	7.9	10.0	11.0	11.9
I_2	…	…	0	3.2	5.2	7.8	11.7	13.7
I_1	…	…	…	0	1.9	4.1	8.2	11.8

2.5 Application of the Willems method

When determining age with the Willems method, we applied the mineralization phases of the seven left mandibular teeth, namely stages A–H from the Demirjian method [5] (Fig. 1). By using standard score tables separately prepared for males and females, the individual's estimated dental age was calculated from the total of these numerical values (Tables 5,6).

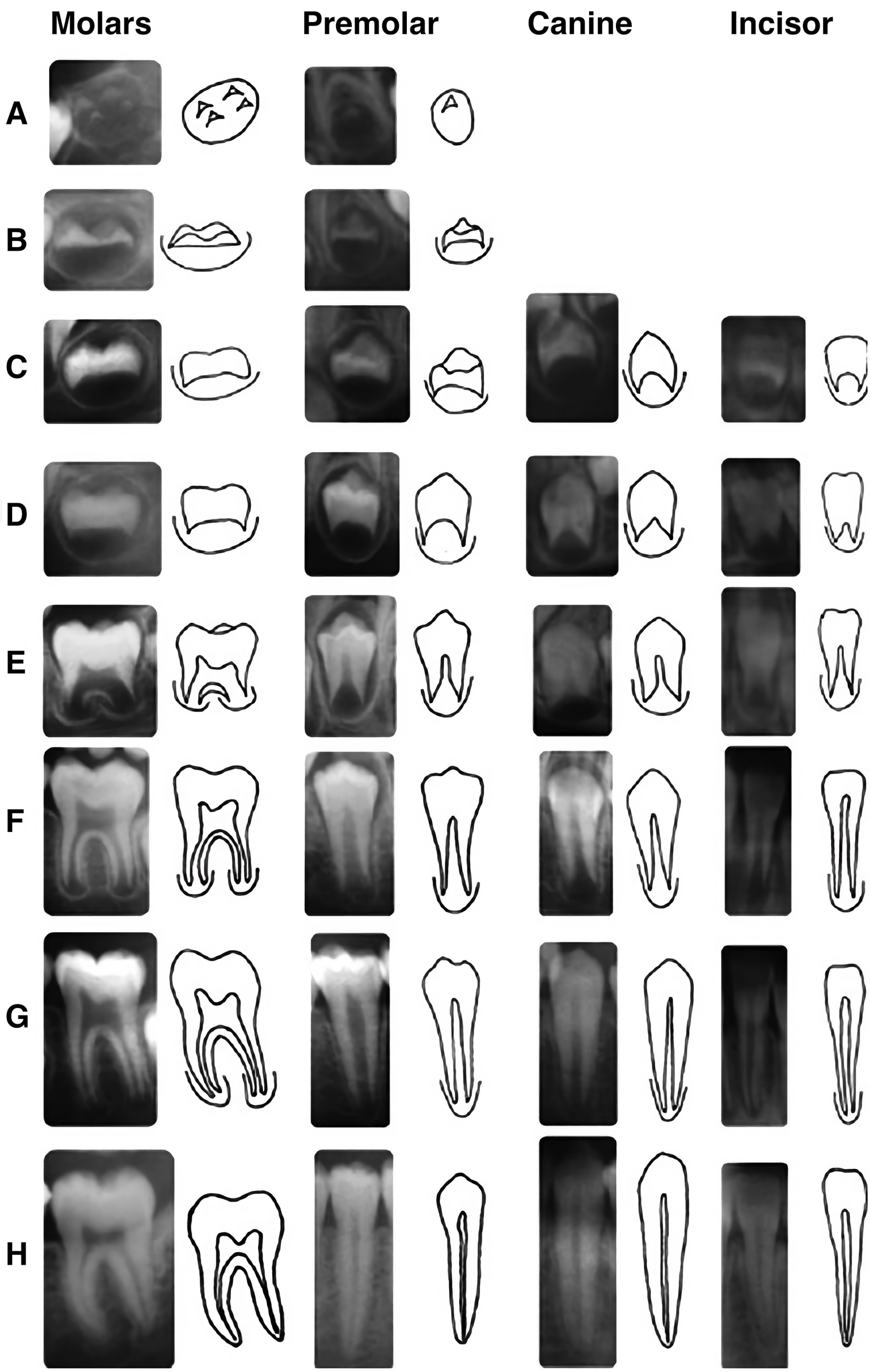

FIGURE 1. **Tooth development stages according to the Demirjian method (A–H) [4].**

TABLE 2. Scoring table for the Demirjian method for females [4].

Tooth	A	B	C	D	E	F	G	H
M_2	2.7	3.9	6.9	11.1	13.5	14.2	14.5	15.6
M_1	…	…	0	4.5	6.2	9.0	14.0	16.2
PM_2	1.8	3.4	6.5	10.6	12.7	13.5	13.8	14.6
PM_1	…	0	3.7	7.5	11.8	13.1	13.4	14.1
C	…	…	0	3.8	7.3	10.3	11.6	12.4
I_2	…	…	0	3.2	5.6	8.0	12.2	14.2
I_1	…	…	…	0	2.4	5.1	9.3	12.9

2.6 Calculation and analysis of pulp and tooth volumes on CBCT images using MIMICS software

When determining volume measurements of pulp and teeth from CBCT data, we selected the mandibular left permanent 1st molars. CBCT images were acquired in DICOM (Digital Imaging and Communications in Medicine) format using the i-CAT® (Model 17–19, Imaging Sciences International, Hatfield, PA, USA) device. The volumes of teeth and pulp in the created images were determined by three-dimensional modeling software (MIMICS) for the necessary analysis (Fig. 2).

2.7 Creation of three-dimensional images

Three-dimensional images of the tooth and pulp present in three different cross-sectional two-dimensional (2D) images were constructed (Figs. 3,4). After creating the 3D models, volume values for both the tooth and the pulp were obtained (Fig. 5).

2.8 Statistical analysis

In our preliminary analysis, we estimated the sample size required by our research. The sample width was calculated using the G*Power V. 3.1.9.6 program (Heinrich Heine University, Düsseldorf, Germany). Considering the differences between the Demirjian and Willems age estimation methods and chronological ages; with 95% confidence $(1-\alpha)$, 95% test power $(1-\beta)$, and an effect size of $d = 0.49$, the required case count for the study was determined to be 56. Upon reviewing reference studies related to age estimation performed using pulp volume and the pulp/tooth volume ratio according to the regression analysis method, with 95% confidence $(1-\alpha)$, 95% test power $(1-\beta)$, and $f^2 = 0.203$, the required case count for the study was determined to be 66. According to *post-hoc* power analysis, the test power was determined to be 99.4%. After reviewing the data in the literature, the sample size for our study was set at 100. The data were analyzed with IBM SPSS version 23 software (IBM SPSS Inc., Armonk, NY, USA). For the Demirjian and Willems methods, after the first set of measurements, we repeated measurements of randomly selected cases under the same conditions four weeks later (the 2nd measurement). The intra-class correlation coefficient was used to investigate the agreement between the measurements. Next, the compliance with the normal distribution was

TABLE 3. Dental development score table according to the Demirjian method for males [4].

Age	Score	Age	Score	Age	Score	Age	Score
3.0	12.4	7.0	46.7	11.0	92.0	15.0	97.6
0.1	12.9	0.1	48.3	0.1	92.2	0.1	97.7
0.2	13.5	0.2	50.0	0.2	92.5	0.2	97.8
0.3	14.0	0.3	52.0	0.3	92.7	0.3	97.8
0.4	14.5	0.4	54.3	0.4	92.9	0.4	97.9
0.5	15.0	0.5	56.8	0.5	93.1	0.5	98.0
0.6	15.6	0.6	59.6	0.6	93.3	0.6	98.1
0.7	16.2	0.7	62.5	0.7	93.5	0.7	98.2
0.8	17.0	0.8	66.0	0.8	93.7	0.8	98.2
0.9	17.6	0.9	69.0	0.9	93.9	0.9	98.3
4.0	18.2	8.0	71.6	12.0	94.0	16.0	98.4
0.1	18.9	0.1	73.5	0.1	94.2		
0.2	19.7	0.2	75.1	0.2	94.4		
0.3	20.4	0.3	76.4	0.3	94.5		
0.4	21.0	0.4	77.7	0.4	94.6		
0.5	21.7	0.5	79.0	0.5	94.8		
0.6	22.4	0.6	80.2	0.6	95.0		
0.7	23.1	0.7	81.2	0.7	95.1		
0.8	23.8	0.8	82.0	0.8	95.2		
0.9	24.6	0.9	82.8	0.9	95.4		
5.0	25.4	9.0	83.6	13.0	95.6		
0.1	26.2	0.1	84.3	0.1	95.7		
0.2	27.0	0.2	85.0	0.2	95.8		
0.3	27.8	0.3	85.6	0.3	95.9		
0.4	28.6	0.4	86.2	0.4	96.0		
0.5	29.5	0.5	86.7	0.5	96.1		
0.6	30.3	0.6	87.2	0.6	96.2		
0.7	31.1	0.7	87.7	0.7	96.3		
0.8	31.8	0.8	88.2	0.8	96.4		
0.9	32.6	0.9	88.6	0.9	96.5		
6.0	33.6	10.0	89.0	14.0	96.6		
0.1	34.7	0.1	89.3	0.1	96.7		
0.2	35.8	0.2	89.7	0.2	96.8		
0.3	36.9	0.3	90.0	0.3	96.9		
0.4	38.0	0.4	90.3	0.4	97.0		
0.5	39.2	0.5	90.6	0.5	97.1		
0.6	40.9	0.6	90.8	0.6	97.2		
0.7	42.0	0.7	91.3	0.7	97.3		
0.8	43.6	0.8	91.6	0.8	97.4		
0.9	45.1	0.9	91.8	0.9	97.5		

TABLE 4. Dental development score table according to the Demirjian method for females [4].

Age	Score	Age	Score	Age	Score	Age	Score
3.0	13.7	7.0	51.0	11.0	94.5	15.0	99.2
0.1	14.4	0.1	52.9	0.1	94.7	0.1	99.3
0.2	15.1	0.2	55.5	0.2	94.9	0.2	99.4
0.3	15.8	0.3	57.8	0.3	95.1	0.3	99.4
0.4	16.6	0.4	61.0	0.4	95.3	0.4	99.5
0.5	17.3	0.5	65.0	0.5	95.4	0.5	99.6
0.6	18.0	0.6	68.0	0.6	95.6	0.6	99.6
0.7	18.8	0.7	71.0	0.7	95.8	0.7	99.7
0.8	19.5	0.8	75.0	0.8	96.0	0.8	99.8
0.9	20.3	0.9	77.0	0.9	96.2	0.9	99.9
4.0	21.0	8.0	78.8	12.0	96.3	16.0	100.0
0.1	21.8	0.1	80.2	0.1	96.4		
0.2	22.8	0.2	81.2	0.2	96.5		
0.3	22.5	0.3	82.2	0.3	96.6		
0.4	23.2	0.4	83.1	0.4	96.7		
0.5	24.0	0.5	84.8	0.5	96.8		
0.6	24.8	0.6	84.8	0.6	96.9		
0.7	25.6	0.7	85.3	0.7	97.0		
0.8	26.4	0.8	86.1	0.8	97.1		
0.9	27.2	0.9	86.7	0.9	97.2		
5.0	28.0	9.0	87.2	13.0	97.3		
0.1	28.9	0.1	87.8	0.1	97.4		
0.2	29.7	0.2	88.3	0.2	97.5		
0.3	30.5	0.3	88.8	0.3	97.6		
0.4	31.3	0.4	89.3	0.4	97.7		
0.5	32.1	0.5	89.8	0.5	97.8		
0.6	33.0	0.6	90.2	0.6	98.0		
0.7	34.0	0.7	90.7	0.7	98.1		
0.8	35.1	0.8	91.1	0.8	98.2		
0.9	36.8	0.9	91.4	0.9	98.3		
6.0	37.0	10.0	91.8	14.0	98.3		
0.1	38.0	0.1	92.1	0.1	98.4		
0.2	39.1	0.2	92.3	0.2	98.5		
0.3	40.2	0.3	92.6	0.3	98.6		
0.4	41.3	0.4	92.9	0.4	98.7		
0.5	42.5	0.5	93.2	0.5	98.8		
0.6	43.9	0.6	93.5	0.6	98.9		
0.7	46.7	0.7	93.7	0.7	99.0		
0.8	48.0	0.8	94.0	0.8	99.1		
0.9	49.5	0.9	94.2	0.9	99.1		

tested by the Shapiro-Wilk and Kolmogorov-Smirnov tests. The paired sample *t*-test was used to compare normally distributed quantitative data for two dependent groups, while the Wilcoxon test was used for non-normally distributed data. All measurements and additional information (an individual's age and gender, pulp volume and ratio of pulp/tooth volume) were entered into a spreadsheet (Microsoft Excel, Microsoft, Seattle, USA). Regression equations and linear regression analysis were then used to create age estimates from pulp volume and pulp/tooth volume ratio. Analysis results were presented as mean ± standard deviation and median (minimum–maximum) for quantitative data. When interpreting the results, a significance level of 0.05 was used; if p was < 0.05, there was a significant relationship; if p was > 0.05, there was no significant relationship.

3. Results

In our study cohort, 53% of the participants were male and 47% were female (Table 7). Both males and females exhibited statistically significant agreements between the first and second measurements of the Demirjian and Willems age values. For males, the agreements were as follows: Demirjian age values ICC (Intraclass Correlation Coefficient) = (0.997; $p < 0.001$) and Willems age values (ICC = 0.996; $p < 0.001$). Females showed similar results for both Demirjian age values (ICC = 0.997; $p < 0.001$) and Willems age values (ICC = 0.996; $p < 0.001$). When considering the entire cohort, excellent agreements persisted for both the Demirjian (ICC = 0.997; $p < 0.001$) and Willems age values (ICC = 0.996; $p < 0.001$).

Detailed data are presented in Table 8.

Table 9 presents a comparison of the difference values between chronological age and the age methods from the Demirjian and Willems. Methods with a difference value closer to 0 provide values closer to the chronological age. There was a difference between the mean age differences "difference 1" and "difference 2" in males ($p < 0.001$). The mean for "difference 1" was −0.52, while the mean for "difference 2" was −0.03. In females, there was a significant difference between the mean age differences "difference 1" and "difference 2" ($p < 0.001$). The mean for "difference 1" was 0.59 while the mean for "difference 2" was −0.12. Without distinguishing by gender, there was a difference between the mean age "difference 1" and "difference 2" ($p < 0.001$). The mean for "difference 1" was −0.56 while the mean for "difference 2" was −0.07.

A simple linear regression model was used to determine a formula to estimate chronological age with the effect of age considered as the dependent variable and the pulp volume considered as the predictive variable. The coefficient of determination (R^2) from this regression analyses were then calculated to evaluate the relationship between chronological age and pulp volume. The standard error (SE) calculated from the regression analyses was then used to determine the accuracy of the mathematical models.

In males, statistical significance was achieved in the regression model constructed to examine the estimated age derived from pulp volume data (F = 19,046, $p < 0.001$). The pulp volume explained 25.8% of the variation in age. An increase of one unit in pulp volume reduced the age value by 0.202 units (p

TABLE 5. Dental mineralization score table for males according to the Willems method [5].

Tooth	A	B	C	D	E	F	G	H
Central Incisor	…	…	1.68	1.49	1.50	18.60	2.07	2.19
Lateral Incisor	…	…	0.55	0.63	0.74	1.08	1.32	1.64
Canine	…	…	…	0.04	0.31	0.47	1.09	1.90
First Premolar	0.15	0.56	0.75	1.11	1.48	2.03	2.43	2.83
Second Premolar	0.08	0.05	0.12	0.27	0.33	0.45	0.40	1.15
First Molar	…	…	…	0.69	1.14	1.60	1.95	2.15
Second Molar	0.18	0.48	0.71	0.80	1.31	2.00	2.48	4.17

TABLE 6. Dental mineralization score table for females according to the Willems method [5].

Tooth	A	B	C	D	E	F	G	H
Central Incisor	…	…	1.83	2.19	2.34	2.82	3.19	3.14
Lateral Incisor	…	…	…	0.29	0.32	0.49	0.79	0.70
Canine	…	…	0.60	0.54	0.63	1.08	1.72	2.00
First Premolar	0.95	0.15	0.16	0.41	0.60	1.27	1.58	2.19
Second Premolar	0.19	0.01	0.27	0.17	0.35	0.35	0.55	2.21
First Molar	…	…	…	0.62	0.90	1.56	1.82	2.21
Second Molar	0.10	0.11	0.21	0.32	0.66	1.28	2.09	4.04

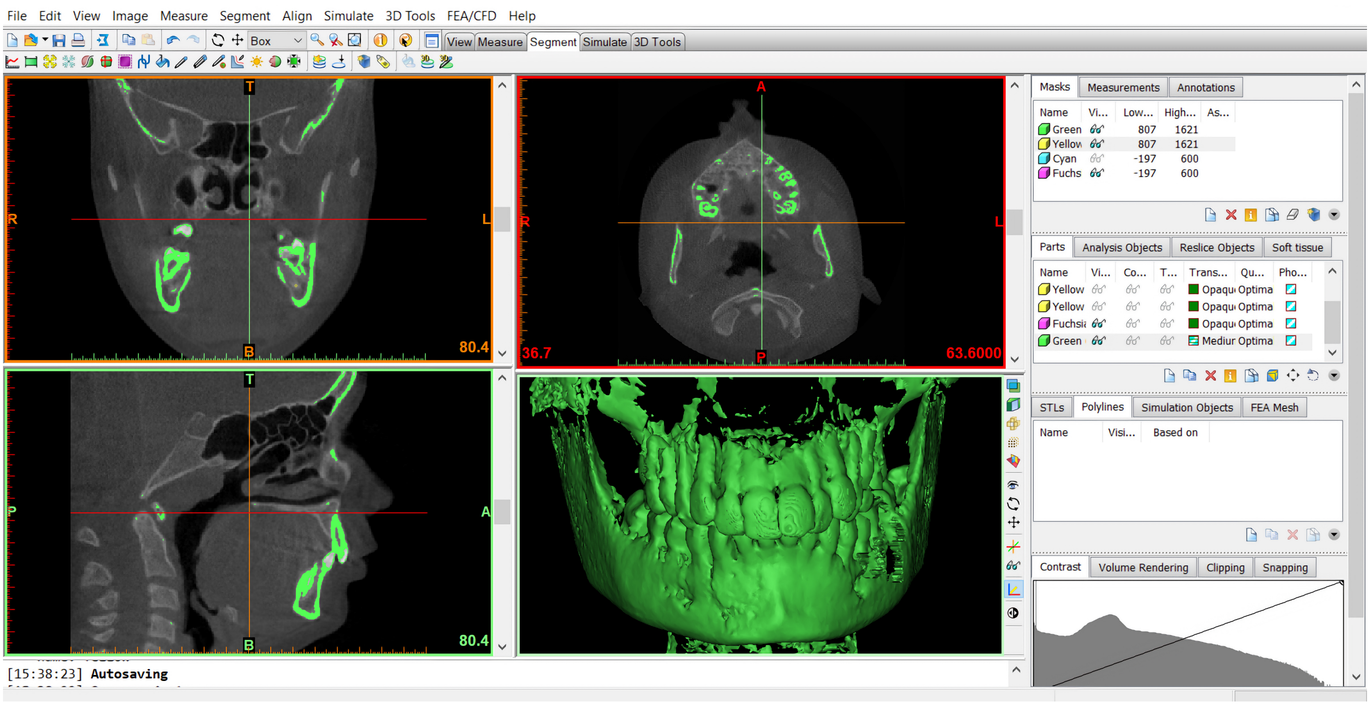

FIGURE 2. Display of the MIMICS software working screen (coronal, axial, sagittal sections, and three-dimensional image viewing).

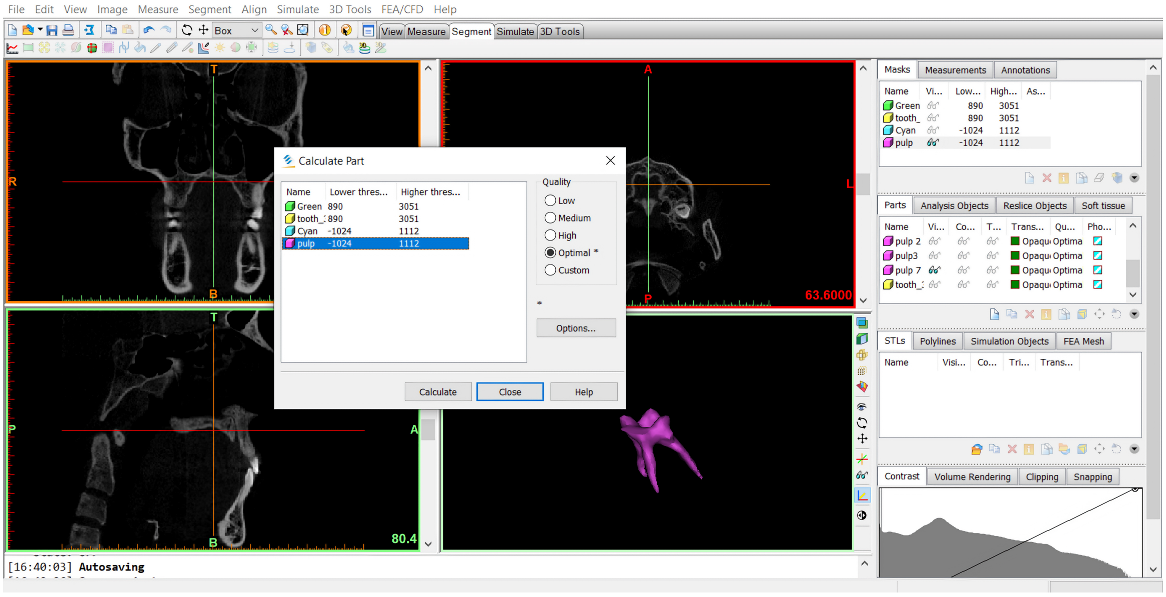

FIGURE 3. Creation of a three-dimensional (3D) image (3D pulp image).

FIGURE 4. Creation of a three-dimensional (3D) image (3D mandibular 1st molar tooth image).

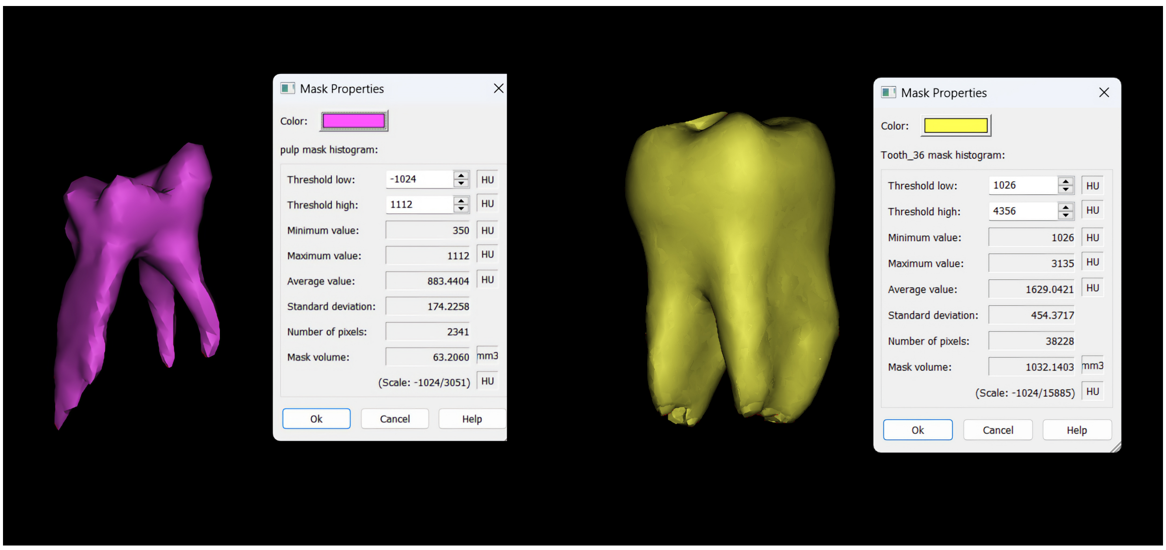

FIGURE 5. Calculation of the volumes for pulp and teeth.

TABLE 7. Distribution of gender.

Gender	n	%
Female	47	47
Male	53	53

< 0.001). In addition, the standard error value for pulp volume was 0.046 (Table 10).

The equation derived from the regression analysis for age estimation is shown in Eqn. (1).

$$Age\ (Male)\ =\ 26.084\ -\ (0.202\ \times\ Pulp\ volume)$$

In females, no statistical significance was observed in the regression model constructed to examine the estimated age derived from pulp volume data ($F = 0.732$, $p = 0.397$). Since this was not a significant model, no regression equation was formulated (Table 10).

For all individuals, statistical significance was achieved in the regression model constructed to examine the estimated age derived from pulp volume data ($F = 11.704$, $p < 0.001$). The pulp volume explained 9.8% of the variation in age. An increase of one unit in pulp volume reduced the age value by 0.122 units ($p < 0.001$). In addition, the standard error value for pulp volume was 0.036 (Table 10, Fig. 6).

The equation derived from the regression analysis derived for age estimation is shown in Eqn. (2).

$$Age\ (Total)\ =\ 20.379\ -\ (0.122\ \times\ Pulp\ volume)$$

First, the pulp volume and tooth volume of each tooth was measured and then the pulp/tooth volume ratio was calculated. A simple linear regression model, with the effect of age considered as the dependent variable and the pulp/tooth volume ratio considered as the predictive variable, was used to determine the formula to estimate chronological age. The coefficient of determination (R^2) from the regression analyses was calculated to evaluate the relationship between chronological age and pulp/tooth volume ratio. The standard error (SE) calculated from the regression analyses was used to determine the accuracy of the mathematical models.

In males, statistical significance was obtained in the regression model constructed for the estimation of age from the Pulp/Tooth volume ratio data ($F = 41.489$, $p < 0.001$). The Pulp/Tooth volume ratio explained 43.8% of the variance in age. An increase of one unit in the Pulp/Tooth volume ratio reduced the age value by 175.699 units ($p < 0.001$).

Furthermore, the standard error for the Pulp/Tooth volume ratio was 27.277 (Table 11).

The equation derived from the regression analysis derived for age estimation is shown in Eqn. (3).

$$Age\ (Male) = 22.845 - (175.699 \times Pulp/Tooth\ volume\ ratio)$$

In females, statistical significance was achieved in the regression model constructed for the estimation of age from the Pulp/Tooth volume ratio data ($F = 27.057$, $p < 0.001$). The Pulp/Tooth volume ratio accounted for 36.2% of the variance in age. An increase of one unit in the Pulp/Tooth volume ratio reduced the age value by 179.213 units ($p < 0.001$). The standard error for the Pulp/Tooth volume ratio was 34.453 (Table 11).

The equation derived from the regression analysis derived for age estimation is shown in Eqn. (4).

$$Age\ (Female)\ =\ 23.554 - (179.213 \times Pulp/Tooth\ volume\ ratio)$$

For all individuals, without distinguishing by gender, statistical significance was obtained in the regression model created for the estimation of age from the Pulp/Tooth volume ratio data ($F = 65.76$, $p < 0.001$). The Pulp/Tooth volume ratio explained 39.5% of the variance in age. An increase of one unit in the Pulp/Tooth volume ratio reduced the age value by 172.954 units ($p < 0.001$). The standard error associated with the Pulp/Tooth volume ratio was 21.328 (Table 11, Fig. 7).

The equation from the regression analysis derived for age estimation is given in Eqn. (5).

$$Age\ (Total)\ =\ 22.902 - (172.954 \times Pulp/Tooth\ volume\ ratio)$$

4. Discussion

Forensic odontology plays a pivotal role in accurately assessing and presenting dental findings. The applications of this methodology are diverse and range from identifying both the living and deceased based on age, gender, and racial markers to matters involving malpractice, negligence and child abuse. In fact, dental records are instrumental for personal identification, with teeth often serving as invaluable assets given their resilience to mechanical, chemical, and temporal degradation [11, 12]. Given the significance of teeth in identity determination, our study focused on dental age determination methods, and compared the efficacy of various age calculation techniques. The radiographic development of teeth, the timelines of tooth eruption, or degrees of calcification are commonly used methods for determining dental age. These methods provide accurate results when compared with a standard measurement. Dental age assessment facilitates decision making processes related to treatment procedures in both pediatric dentistry and orthodontics [13]. For our research, relevant radiographs were evaluated by a pediatric dentist with 5 years of clinical expertise. Then, we analyzed age data extracted from CBCT and compared this data with established radiological dental age determination standards set by Demirjian and Willems. It is worth noting that in the realm of forensic odontology, periapical and panoramic radiography are the go-to techniques. Of these, panoramic radiographs are particularly favored by researchers due to their comprehensive scope, capturing all teeth in a single image. This makes them an optimal choice for age estimation in children, especially considering that potential distortions in intraoral radiographs

TABLE 8. Comparison between the first and second measurements from the Demirjian and Willems age estimation methods.

	1. Measurement		2. Measurement		Test Sta.	*p*	ICC (95% CI)	*p*
Gender	Mean ± SD	Median (min.–max)	Mean ± s. deviation	Median (min.–max)				
Male								
Demirjian	12.56 ± 2.36	12.50 (8.50–16.00)	12.58 ± 2.33	12.50 (9.00–16.00)	*Z* = −0.753	0.451	0.997 (0.994–0.998)	<0.001
Willems	12.06 ± 2.24	11.90 (8.40–16.00)	12.08 ± 2.21	11.90 (8.50–16.00)	*t* = −0.348	0.729	0.996 (0.993–0.998)	<0.001
Female								
Demirjian	12.72 ± 2.09	13.00 (8.70–16.00)	12.76 ± 2.05	13.00 (8.60–16.00)	*t* = −1.478	0.146	0.997 (0.995–0.999)	<0.001
Willems	12.27 ± 2.18	12.20 (8.10–16.40)	12.26 ± 2.20	12.00 (8.10–16.40)	*t* = 0.446	0.658	0.996 (0.994–0.998)	<0.001
Total								
Demirjian	12.63 ± 2.23	12.60 (8.50–16.00)	12.67 ± 2.19	12.65 (8.60–16.00)	*Z* = −1.150	0.250	0.997 (0.996–0.998)	<0.001
Willems	12.16 ± 2.20	12.00 (8.10–16.40)	12.16 ± 2.20	11.90 (8.10–16.40)	*t* = 0.037	0.970	0.996 (0.994–0.997)	<0.001

SD: Standard deviation; t: Paired-samples t-test statistic; Z: Wilcoxon test statistic; ICC (95% CI): Intraclass correlation coefficient (95% confidence interval).

TABLE 9. Comparison of difference values between chronological age and the Demirjian and Willems methods.

	Difference 1 (Chronological age-Demirjian)		Difference 2 (Chronological age-Willems)		Test Statistic	*p*
	Mean ± s. deviation	Mean (min.–max.)	Mean ± SD	Mean (min.–max.)		
Gender						
Male	−0.52 ± 0.83	−0.50 (−2.60–1.00)	−0.03 ± 0.72	0.00 (−1.75–1.20)	*t* = −6.258	<0.001
Female	−0.59 ± 0.98	−0.40 (−2.65–1.55)	−0.12 ± 0.97	−0.15 (−2.40–2.45)	*t* = −5.641	<0.001
Total	−0.56 ± 0.90	−0.50 (−2.65–1.55)	−0.07 ± 0.85	0.00 (−2.40–2.45)	*t* = −8.465	<0.001

SD: Standard deviation; t: Paired-samples t-test statistic.

TABLE 10. Regression model and analysis of estimated age derived from pulp volume data.

	$\beta 1$ (95% CI)	SE	$\beta 2$	*t*	*p*	Zero	Partial	Part	VIF
Male									
Constant Pulp	26.084 (19.605–32.562)	3.227		8.083	<0.001				
Volume	−0.202 (−0.295–−0.109)	0.046	−0.521	−4.364	<0.001	−0.521	−0.521	−0.521	1.000
Female									
Constant Pulp	15.418 (7.685–23.151)	3.839		4.016	<0.001				
Volume	−0.049 (−0.166–0.067)	0.058	−0.127	−0.856	0.397	−0.127	−0.127	−0.127	1.000
Total									
Constant Pulp	20.379 (15.554–25.203)	2.431		8.382	<0.001				
Volume	−0.122 (−0.192–−0.051)	0.036	−0.327	−3.421	0.001	−0.327	−0.327	−0.327	1.000

Male ($F = 19.046$, $p < 0.001$, $R^2 = 0.272$, adjusted $R^2 = 0.258$, Durbin-Watson = 1.388); Female ($F = 0.732$, $p = 0.397$, $R^2 = 0.016$, adjusted $R^2 = -0.006$, Durbin-Watson=1.96); Total ($F = 11.704$, $p < 0.001$, $R^2 = 0.107$, adjusted $R^2 = 0.098$, Durbin-Watson = 1.7); $\beta 1$: Unstandardized beta coefficient; $\beta 2$: Standardized beta coefficient; SE: Standard error; VIF (Variance Inflation Factor); CI: Confidence Interval.

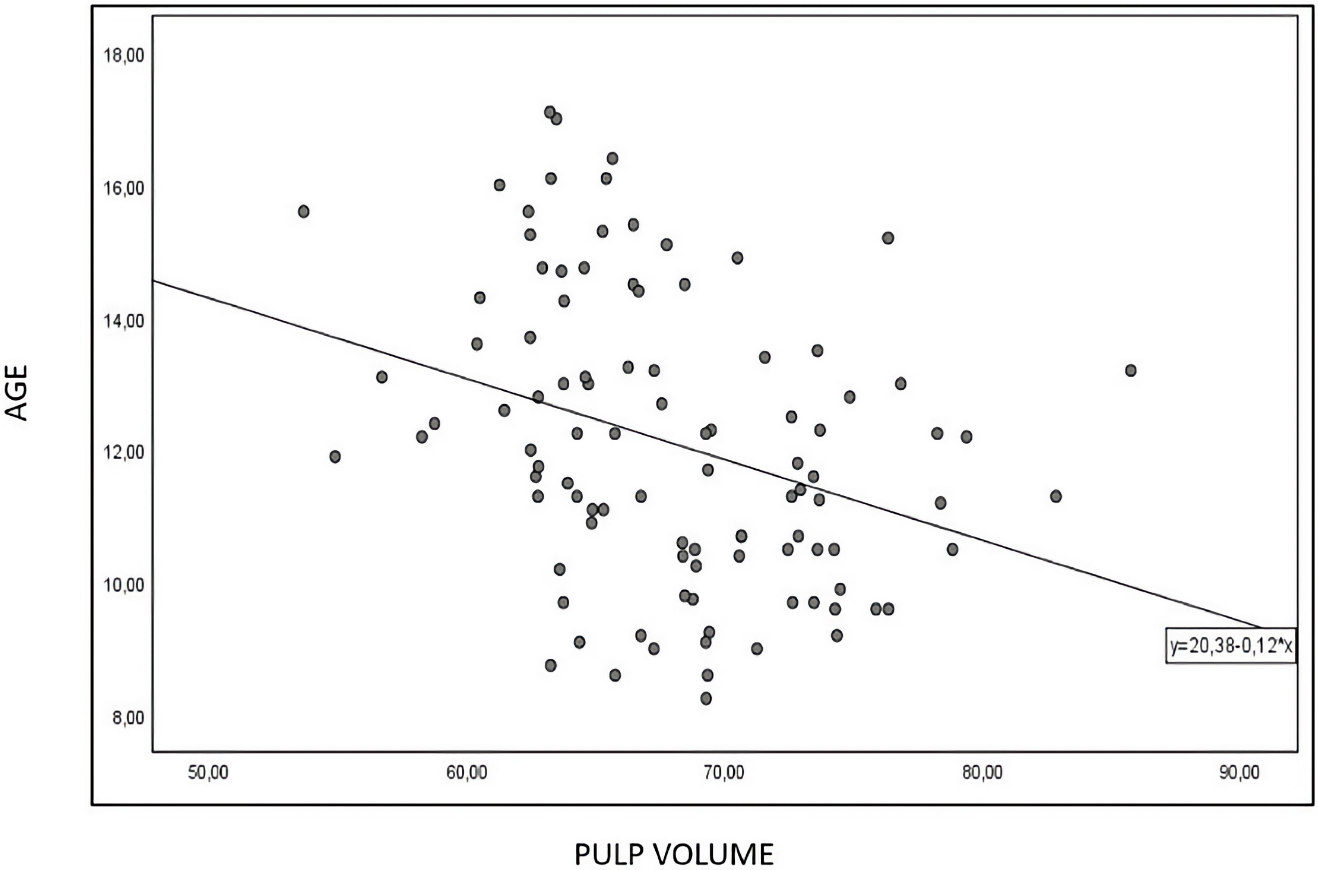

FIGURE 6. Distribution of the relationship between pulp volume and age for all individuals.

TABLE 11. Regression model and analysis of estimated age derived from the pulp/tooth volume ratio data.

	β1 (95% CI)	SE	β2	*t*	*p*	Zero	Partial	Part	VIF
Male									
Constant	22.845 (19.449–26.241)	1.692		13.505	<0.001				
Pulp/tooth volume ratio	−175.699 (−230.461–−120.938)	27.277	−0.670	−6.441	<0.001	−0.670	−0.670	−0.670	1.000
Female									
Constant	23.554 (19.106–28.002)	2.209		10.665	<0.001				
Pulp/tooth volume ratio	−179.213 (−248.605–−109.821)	34.453	−0.613	−5.202	<0.001	−0.613	−0.613	−0.613	1.000
Total									
Constant	22.902 (20.235–25.568)	1.344		17.043	<0.001				
Pulp/tooth volume ratio	−172.954 (−215.279–−130.630)	21.328	−0.634	−8.109	<0.001	−0.634	−0.634	−0.634	1.000

Male ($F = 41.489$, $p < 0.001$, $R^2 = 0.449$, Adjusted $R^2 = 0.438$, Durbin-Watson = 1.124); Female ($F = 27.057$, $p < 0.001$, $R^2 = 0.375$, Adjusted $R^2 = 0.362$, Durbin-Watson = 1.704); Total ($F = 65.76$, $p < 0.001$, $R^2 = 0.402$, Adjusted $R^2 = 0.395$, Durbin-Watson = 1.408), β1: Unstandardized beta coefficient; β2: Standardized beta coefficient; SE: Standard error; VIF: Variance inflation factor; CI: Confidence Interval.

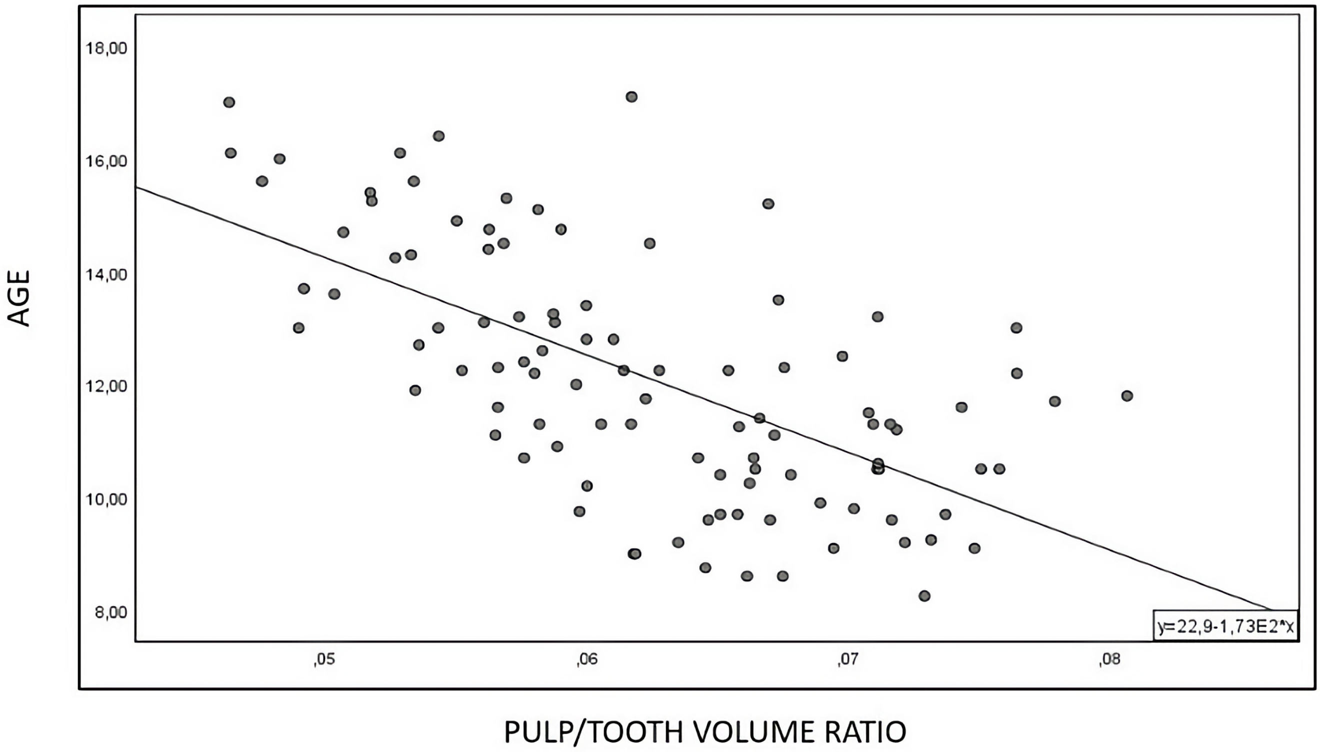

FIGURE 7. Distribution of the relationship between the Pulp/Tooth volume ratio and age for all individuals.

can skew evaluations. That said, CBCT, a relatively new entrant, offers a distinct advantage over both periapical and panoramic radiography. This edge is attributed to its 3D multi-slice imaging capability, which generates a more nuanced view of morphological features [14–18]. Therefore, in our research, panoramic radiographs with high applicability and accessibility in children and adolescents were preferred and CBCT, which provides the examination of 3D images and is increasingly used for dental age determination in recent years, was included. Unlike traditional panoramic radiographs that produce 2D images, CBCT scans reduce errors such as the superimposition and distortion of anatomical structures, thus providing clearer and more accurate information. However, when comparing CBCT with panoramic radiography, it is important to consider that despite offering more diagnostic information, CBCT also exposes patients to a higher radiation dose and risk. Care should be taken to not unnecessarily increase the risk to patients while enhancing diagnostic yield [19]. In pediatric dentistry, the use of a wide field of view (FOV) should be avoided. Nevertheless, the use of such scans can be justified in certain situations, such as orthodontic analysis, cleft lip and palate rehabilitation, and analysis of the upper airways [20, 21].

In our study, the feasibility of using cone beam computed tomography (CBCT), which can provide information related to 3D tooth volume, as a new alternative method was investigated in cases where traditional methods of dental age analysis performed with panoramic radiographs proved insufficient for age estimation. Additional CBCT scans were not performed for the purpose of age estimation. Existing radiographic records created for the diagnosis and treatment of patients with suspected maxillofacial trauma, for orthognathic surgery planning, or for cleft lip and palate, were also included. Necessary protective measures were taken and the devices were appropriately positioned for each individual while these radiographic records were being obtained. Volumetric measurements in CBCT are dependent on voxel size. Smaller voxel sizes provide more accurate results but result in higher radiation doses. Therefore, despite the need for high resolution images to obtain accurate data, this can lead to high radiation doses [22]. Oenning *et al.* [23] proposed a new approach which they named "As Low as Diagnostically Acceptable, Indication-Specific, and Patient-Centric" (ALADAIP). This principle suggests obtaining images using radiation doses that are compatible with current imaging methods that are indication-specific and patient-centric.

In CBCT, voxels have the same length on the X, Y and Z axes. Voxel sizes generally range from 0.07 to 0.40 mm. In dental applications, the choice of voxel size is dictated by the specifics of clinical cases. At present, there is no universally accepted protocol for this selection [24]. Taking cues from the existing literature and considering the age demographics of our study participants, we noted that the voxel size of the CBCT images in our collection was 0.3 mm, thus aligning with the aforementioned range. A review of recent systematic studies and meta-analyses concerning dental age estimation through pulp and tooth volume revealed a specific pattern in that evaluations frequently targeted single-rooted teeth and those situated in the anterior region. Notably, the strongest correlation between age and volumetric data emerged in the mandibular 1st molars, while the weakest was seen in the mandibular third molars. This discrepancy is believed to have arisen from the limited research centered on multi-rooted teeth and the intrinsic significance of the permanent 1st molar;

this is the inaugural permanent tooth to surface and plays a pivotal role in occlusion [25, 26]. We aimed to expand upon the existing literature by selecting the left mandibular 1st molar teeth for pulp and tooth volume measurement. Multiple image-enhancing software tools are utilized to perform three-dimensional measurements of the pulp chamber. However, MIMICS software processes images from scanned data into 3D surface models, 3D designs, and 3D measurements more efficiently than other forms of software. Yet, this software struggles to detect minute structural details, especially in the radicular portion of the tooth. Therefore, during the data slice editing phase in the software, manual intervention is required for the radicular aspect [27]. These reasons prompted our selection of MIMICS software in our study, where necessary manual adjustments were made during the segmentation phase for accurate analysis of the pulp and tooth volume. The segmentation of images formed at every third slice was completed under controlled conditions. Previous research by Biuki *et al.* [28] and Yang *et al.* [29] also reported volumetric data derived in DICOM format using the MIMICS software program. In our study, CBCT images were obtained using the i-CAT® device, and volumetric data was generated in DICOM format by the MIMICS software program, thus aligning our methods with the existing literature.

In previous studies related to dental age determination, initial measurements were made on panoramic radiographs for Demirjian and Willems methods by the same observer. Four weeks later, second measurements were repeated on randomly chosen cases; this revealed statistically significant and excellent congruence between the age values obtained [30, 31]. The statistical outcomes of our study align with the existing literature, thus confirming the excellent congruence between age values for both measurements. A previous study by Djukic *et al.* [32] found that the Demirjian method overestimated tooth age by an average of 0.45 in males and 0.42 in females, while the Willems method overestimated tooth age by 0.12 in males and 0.16 in females. In another study, Altan *et al.* [33] revealed that the Demirjian method overestimated tooth age by 0.832 in females and 0.923 in males, whereas the Willems method overestimated tooth age by 0.202 in females and 0.434 in males. Another study showed that the tooth age determined by the Demirjian method was on average 0.53 ± 1.08 years higher for males and 0.54 ± 1.05 years higher for females. In contrast, with the Willems method, tooth age was 0.03 ± 0.91 years higher for males and 0.03 ± 0.90 years higher for females [34]. In our present study, we found that the Demirjian method overestimated chronological age by 0.52 ± 0.83 years in males and 0.59 ± 0.98 years in females; these differences were statistically significant. The Willems method overestimated tooth age by 0.03 ± 0.72 years in males and 0.12 ± 0.97 years in females; however, this difference was not statistically significant. Although both the Demirjian and Willems methods provided higher estimates than the chronological age, the Willems method was closer to the chronological age. Research conducted in Turkey [35] assessing the validity of the Demirjian and Willems methods found that the Demirjian method provided higher age estimates than chronological age, while the Willems method provided more accurate predictions. Our findings concur with these results.

A meta-analysis by Boedi *et al.* [25] stated that in 13 studies, dental age determination calculations based on CBCT image data utilized the pulp/tooth volume ratio, while two studies utilized the pulp volume data for necessary analysis and examinations. Our research considered these findings in the literature, analyzing both the pulp volume and the pulp/tooth volume ratio to examine their effects on dental age determination.

In a study conducted by Hidayat *et al.* [36], regression analyses revealed that a regression equation created with age and pulp volume data had an R^2 value of 0.75 for all individuals and provided statistically significant results ($p < 0.001$). This implies that age estimation using pulp volume can represent only 75.3% of volumetric data. As the pulp volume of the canine tooth decreases, the age increases, thus indicating a reduction in pulp space and an increase in dentin thickness. These findings suggest the feasibility of using a pulp volume-based regression model for age estimation [36]. In another study, the pulp volume of the mandibular 1st molars in women was identified as a decisive factor on age, with an R^2 value of 0.169 in women and 0.047 in men. Gender creates a statistically significant difference in pulp volume, and the highest accuracy rates for age estimation were detected in the mandibular 1st molars in women [37]. Upon examining our data, statistically significant results were achieved in the regression model assessing estimated age from pulp volume data in men ($p < 0.001$, $R^2 = 0.258$); thus, 25.8% of age variation can be explained by pulp volume in men. However, in women, no statistical significance was found ($p = 0.397$, $R^2 = -0.006$). For all individuals, there was a statistical significance ($p < 0.001$, $R^2 = 0.098$), with pulp volume explaining 9.8% of the age variation. We observed a stronger correlation in men than in women with a negative correlation, thus indicating that as pulp volume decreases, age increases. Therefore, our findings align with the existing literature.

Previous research by Tardivo *et al.* [38] obtained an R^2 value of 0.38 for all individuals in their regression equation. When evaluated by gender, men had an R^2 value of 0.47, while women had an R^2 value of 0.32. These results indicate that equations based on the Pulp/Tooth Volume ratio predict chronological age more accurately in men [38]. A study by Elmoazen *et al.* [39] reported no statistically significant difference in the Pulp/Tooth volume ratios of the mandibular canine tooth between men and women; the regression equation for all individuals had an R^2 value of 0.755; 0.78 for men and 0.723 for women. The findings reported by Biuki *et al.* [28] aligned with previous studies, thus confirming a negative correlation between age and Pulp/Tooth volume ratios in all evaluated teeth. A stronger correlation was observed in men and was particularly evident in the maxillary central incisors and canine teeth [28]. In our study, for men, the regression model using the Pulp/Tooth volume ratio data yielded an R^2 value of 0.438, thus explaining 43.8% of the age variation ($p < 0.001$). For women, the R^2 value was 0.362, explaining 36.2% of the age variation ($p < 0.001$). For all individuals, the R^2 value was 0.395, explaining 39.5% of the age variation ($p < 0.001$). Again, a stronger correlation was observed in men. Our findings are therefore consistent with existing literature.

Our study featured limitations relating to the upper age limits of the Demirjian and Willems methods for dental age estimation in the 9–16 years age group. Furthermore, the inclusion of the mandibular 1st molars in pulp and tooth volume-based age analysis presents challenges due to early tooth loss, decay or restoration, thus limiting volumetric measurements. Furthermore, the limited sample size in the pediatric age group resulted in an uneven age distribution; this represented another limitation.

5. Conclusions

Our current findings suggest that both methods evaluating data from panoramic radiographs provide higher age estimation values. However, the Willems method yields values closer to chronological age, thus making it a more valid option in our region. Based on CBCT data, age estimation using pulp and tooth volume data is feasible for the pediatric age group. The age estimation created using the Pulp/Tooth volume ratio data yields values closer to chronological age than using just pulp volume data. A stronger correlation was observed in men for both volume data methods. When all methods were separately utilized for age determination, the results from the Willems method were closest to chronological age, marking it a preferable method in terms of applicability and practicality. Further research with a broader sample size is now required for the age estimation method based on pulp and tooth volume data.

AVAILABILITY OF DATA AND MATERIALS

All data generated or analyzed during this study are included in this published article.

AUTHOR CONTRIBUTIONS

YP and SÇ—designed the research study; performed the research; analyzed the data; wrote the manuscript. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This research has been conducted in strict adherence to the Helsinki Declaration. We have procured the necessary ethical clearances with the protocol number 2022-17 dated 30 March 2022 from the Local Ethics Committee of Dicle University Faculty of Dentistry.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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